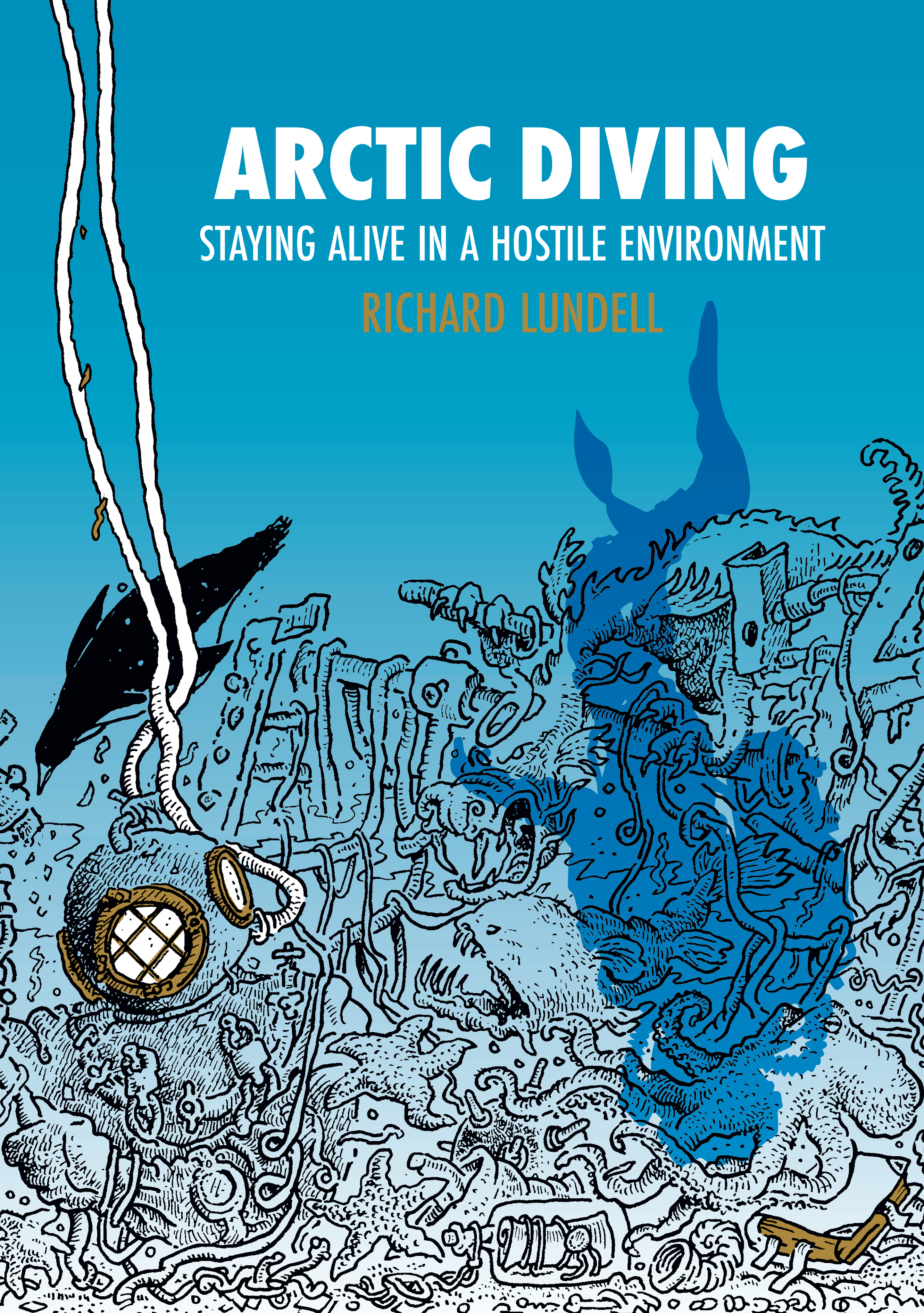
ARCTIC DIVING

STAYING ALIVE IN A HOSTILE ENVIRONMENT

RICHARD LUNDELL



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University of Helsinki
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STAYING ALIVE
IN A HOSTILE ENVIRONMENT

Richard Lundell

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Supervised by
Docent Anne Räisänen-Sokolowski M.D. Ph.D.
Department of Pathology
Helsinki University Hospital and University of Helsinki
Helsinki, Finland

&

Professor Emeritus Kai Parkkola M.D. Ph.D., Capt. Navy ret.
Faculty of Medicine and Health Technology, Tampere University, Tampere, Finland and
National Defence University, Helsinki, Finland

Reviewed by
Docent Matti Mäntysaari, MD, PhD
University of Eastern Finland
Kuopio, Finland

&

Professor Costantino Balestra, PhD
Environmental, Occupational, Ageing (Integrative) Physiology Laboratory
Haute École Bruxelles-Brabant
Brussels, Belgium

Opponent
Associate Professor Jacek Kot, MD, PhD
National Center for Hyperbaric Medicine
Medical University of Gdansk
Gdansk, Poland

Cover illustration: Heikki Paakkanen
Layout: Richard Lundell

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“I cannot command winds and weather” Admiral Nelson

ABSTRACT

In the Arctic diving occurs in cold water throughout the year. At a depth of 20 meters sea/fresh water (msw/mfw) temperatures are 4°C even in the warmest summer. Cold is not only a discomfort factor for divers. It also impairs physical and cognitive performance, which in turn may jeopardize diving safety, and is one of the major risk factors for decompression illness (DCI).

In our study we looked for factors that influence diving safety in Arctic water temperatures and searched for possible ways to reduce the risks. Based on the results from our three studies we aimed to suggest improvements for cold water diving procedures. First, we studied special features of DCI in the Finnish diving population, and different factors associated with DCI. Second, we investigated different thermal protection properties by comparing argon and air used as drysuit inflation gas. Argon is a widely-used passive method to reduce heat loss in cold water diving. Third, we studied the autonomic nervous system (ANS) responses to cold water diving with heart rate variability (HRV) measures. With results from these studies we aimed to give recommendations to make diving in Arctic conditions safer.

We carried out a retrospective study to evaluate DCI treated in Finland over a time period of 20 years (1999-2018). The study included by estimation over 95% of all hyperbaric oxygen-treated DCI patients (n = 571) during the years studied. We divided cases into technical divers (n = 200) and non-technical divers (n = 371) and examined differences between the groups. Technical diving was defined as the usage of mixed breathing gases, closed circuit rebreather diving or planned decompression diving. The mean annual number of treated DCI cases in Finland was 29 (range 16–38). The number of divers treated seemed to show a shift towards technical diving. Technical dives were deeper and longer and were mainly performed in cold water or in an overhead environment. Technical divers were more likely to utilize first aid 100% oxygen (FAO_2) and sought medical attention earlier than non-technical divers. The symptom profiles were similar in both groups. Recompression was performed using US Navy Treatment Table Six (USN TT6) in the majority of the cases and resulted in good final outcomes. Eighty two percent of the patients were asymptomatic on completion of all recompression treatment(s).

To study the difference in thermal insulation properties of argon compared to air we measured the rectal temperature and eight standardized skin temperatures during tests for navy drysuit diving equipment development in Arctic water conditions. Four divers completed 14 dives, each lasting 45 minutes: seven dives used air insulation and seven used argon insulation. From the measured temperatures, changes in the calculated mean body temperature (MBT) were assessed.

There was a significant reduction in the area weighted skin temperature over time (0-45min) during air dives (ΔTskin = -4.16°, SE = 0.445, p<0.001). During argon dives the reduction was significantly smaller compared to the air dives (difference between groups = 2.26°C, SE = 0.358, P<0.001). There were no significant changes in rectal temperatures, nor was a significant difference seen between groups in rectal temperatures.

We investigated the human diving responses in cold water temperatures by retrospectively analyzing repeated 5-minute HRV measures and mean body temperature measurements from dives at regular intervals using naval diving equipment measurement tests in 0°C water. The human body reacts to cold through ANS-mediated thermoregulatory mechanisms. Diving also induces ANS responses as a result of the diving reflex. Three divers performed seven dives without engaging in physical activity (dive time 81–91 min), and two divers performed four dives with physical activity after 10 min of diving (0–10 min HRV recordings were included in the study). Based on changes in the root mean square of successive RR interval differences (RMSSD) an increase in parasympathetic nervous system (PNS) activity could be seen at the beginning of the dive. First from the measure at rest to the measure 0 to 5 min showed a significant increase of 14.67 ms (SE = 6.09, $p = 0.02$). After this PNS activity decreased: the measure from 0 to 5 min to the measure at 5 to 10 min had a significant decrease of 12.92 ms (SE = 6.09, $p = 0.04$). The remaining measures showed an increase in PNS activity over time: the measure from 5 to 10 min until the measure at 75 to 80 min ($n = 7$), showed a significant increase of 97.86 ms (SE = 2.28, $p < 0.001$).

As a conclusion has been a shift towards technical diving in the Finnish diving population, and hence a more demanding types of diving. The number of diagnosed DCI cases in Finland has been quite constant over the last 20 years (1999 to 2018), estimated from a mean incidence of 29 primary decompression treatments annually. Fortunately, the majority of divers recovered well and could continue diving after successful treatment. The use of FAO_2 was relatively uncommon in the treatment of DCI symptoms. Compared to air, argon seemed to have better thermal insulation properties when used as drysuit inflation gas, suggesting it would be beneficial when diving in Arctic conditions. Using argon could make diving safer and reduce the risks of fatal diving accidents. The results of the HRV measures suggested a rapid decrease in parasympathetic activity (PNS) after an initial PNS increase at the beginning of the dive. This decrease in PNS activity has not been described in previous studies. To avoid concurrent sympathetic (SNS) and PNS activity at the beginning of dives, which in turn could increase the risk of malign arrhythmia, we suggest a short adaptation phase before physical activity. Moreover, we suggest it is prudent to pay special attention to cardiovascular risk factors during fit-to-dive evaluations for cold water divers.

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LIST OF PUBLICATIONS

This dissertation is based on the following original articles:

I. Lundell RV, Arola O, Suvilehto J, Kuokkanen J, Valtonen M, Räisänen-Sokolowski A. Decompression illness (DCI) in Finland 1999–2018: Special emphasis on technical diving. Diving and Hyperbaric Medicine, 2019 49(4):259-265.

II. Lundell RV, Wuorimaa T, Räisänen-Sokolowski A, Sundholm JK, Rintamäki H, Rissanen S, Parkkola K. Comparison of argon and air as thermal insulating gases in drysuit dives during military Arctic diving equipment development tests. Undersea and Hyperbaric Medicine, 2019 46(4), 429-435.

III. Lundell RV, Räisänen-Sokolowski A, Wuorimaa T, Ojanen T, Parkkola K. Diving in the Arctic: Cold water immersion's effects on heart rate variability in Navy divers. Frontiers in Physiology, 31 January 2020. https://doi.org/10.3389/fphys.2019.01600.

The articles will be referred to with their Roman numerals in the text. Permission to republish the articles in this dissertation was obtained from the copyright holders.

ABBREVIATIONS

AGE	arterial gas embolism
ANS	autonomic nervous system
BMI	body mass index
CCR	closed circuit rebreather
CMAS	Confédération Mondeale des Activitiés Subaquatiques
CNS	central nervous system
DAN	Diver's Alert Network
DCI	decompression illness
DCS	decompression sickness
EAN	Enriched Air Nitrox
ECG	electrocardiogram
FAO2	first aid oxygen
GF	gradient factor
HBOT	hyperbaric oxygen therapy
HF	high frequency
HR	heart rate
HRV	heart rate variability
IBI	inter-beat-interval
ID	identifier
IWR	in-water recompression
LF	low frequency
MBT	mean body temperature
mfw	meters fresh water
msw	meters sea water
NFCI	non-freezing cold injury
PFO	patent/persistent foramen ovale
PNS	parasympathetic nervous system
RGBM	Reduced Gas Bubble Model
RMSSD	root mean square of the successive differences
RSA	respiratory sinus arrhythmia
SCUBA	self-contained underwater breathing apparatus

SDNN	standard deviation of NN intervals
SNS	sympathetic nervous system
TP	total power
Trect	rectally measured deep body temperature
Tskin	area weighted skin temperature
USN TT (5, 6 or 9)	US Navy Treatment Table (5, 6 or 9)
VLF	very low frequency
VPM	Varying Permeability Model

1 INTRODUCTION

Arctic water conditions induce special risk factors for divers. At a depth of 20 meters or deeper, water temperatures are 4°C throughout the year in Finland. In winter, the surface of the water is frozen, and, just below the layer of ice, water temperatures may vary from –2 to 0°C in saltwater. Heat loss is not only a factor of discomfort for divers, but it also impairs physical and cognitive performance (Davis et al. 1975), increases the risk of decompression illness (DCI) (Gerth 2015, Pendergast et al. 2015), and may lead to hypothermia. Prolonged exposure to cold may increase the risk of diving accidents and can ultimately lead to major health impairments or even death. Both recreational and occupational divers in Northern Europe dive throughout the year. Even with the best efforts to keep divers warm, heat loss is unavoidable during Arctic diving.

To our knowledge, there are no previous scientific studies that describe what kind of dives Finnish divers perform, what contributing factors are associated with DCI in the Finnish diving community, or what the outcome is after recompression among divers treated for DCI in Finland. The unique characteristic of this diving population is that the majority of dives are performed in Arctic conditions that differ significantly from those in most other parts of the world. Cold is a known risk factor for DCI (Gerth 2015, Pendergast et al. 2015) as it impairs peripheral blood circulation and thus off-gassing of inert breathing gas. Globally the incidence of DCI (per dive) varies from 0.010% to 0.095% in different diver populations (Vann et al. 2011) and was recently reported in a study as 0.0041% for recreational divers (Vann et al. 2011). The gold standard treatment for DCI is recompression in a hyperbaric chamber with the administration of hyperbaric oxygen during the treatment (Vann et al. 2011). Different treatment protocols have been suggested but the most commonly used one includes intermittent breathing of pure medical oxygen at a pressure of 284 kPa (Moon et al. 2008, Bennett et al. 2012). In Finland, the USN TT6, and an extended version of the same table, are the most commonly used. Hyperbaric oxygen treatment (HBOT) decreases the size of inert gas bubbles and removes them by increasing the off-gassing gradient (Vann et al. 2011). It also increases the tissue oxygenation in potentially injured tissues. HBOT for DCI is effective when instituted promptly. Most patients become asymptomatic or have only minor residual symptoms after the treatment (Vann et al. 2011).

As mentioned above, in Finnish diving conditions heat loss is unavoidable. There have been several approaches to reduce heat loss in drysuit diving. These include insulating layers under the drysuit and special active warming systems, such as vests, warming gloves and warming shoes.

Such warming systems may be effective for short periods, but they can be unwieldy and clumsy, and they can cause burns to the skin (Valaik et al. 1997). Furthermore, they are susceptible to disturbances and there are indications that warming systems may increase the risk of hypothermia under certain conditions (O'Connor et al. 2009). During military combat diving operations, it may be detrimental to use active warming components, since they can lead to a greater risk of being observed by the enemy due to the heat signature they generate. One regularly used method by some technical divers is to apply argon as a drysuit insulation gas. In theory, argon is a better insulating gas than air because its heat conductivity is 31% lower than the heat conductivity of air (Nuckols et al. 2008). Although the use of argon as a drysuit insulating gas is nothing new for the technical diving community, only two studies have been done to compare argon and air as thermal insulating gases in drysuit diving (Risberg et al. 2001, Vrijdag et al. 2013). Neither demonstrated a difference between the two gases in preventing heat loss.

When exposed to cold the human body reacts with physiological thermoregulation mechanisms such as skin and peripheral tissue circulation vasoconstriction and shivering (Madden et al. 2018). Human thermoregulation mechanisms are mediated through the autonomic nervous system (ANS) (Morrison et al. 2016). The ANS responses to cold are well-studied and understood, but immersion also has effects on the ANS (Godek 2020). To our knowledge there are no published studies on these responses when measured during diving in Arctic water temperatures.

The purpose of this study was to describe factors associated with DCI in very cold Arctic temperature water, as well as to investigate other factors that influence diving safety in these challenging waters. We aim to find ways to reduce the risks. With the help of results from three different studies we aimed to suggest recommendations to make Arctic diving safer.

2 REVIEW OF THE LITERATURE

2.1 Thermal status of diving in Arctic conditions

When diving in very cold conditions, divers are subject to severe cooling—therefore it is vital to protect divers from the cold. Cold is not only a factor of discomfort—it reduces manual dexterity, physical and cognitive function (Davis et al. 1975, Bridgman et al. 1990), it increases the risk of DCI (Gerth 2015, Pendergast et al. 2015) and immersion pulmonary oedema (Gempp et al. 2014), and it may lead to hypothermia and even death. Tissue injury due to freezing may occur in extremities, and cases of non-freezing cold injuries (NFCI) have been described (Gerard et al. 2007).

The human body's deep-body temperature is normally 37°C. Even when exposed to very low temperatures the human body's thermoregulatory mechanisms compensate for the temperature loss to keep the deep-body temperature at a constant level. In prolonged exposure even the deep-body temperature starts to decrease. A deep-body temperature of 35°C and lower is defined as hypothermia and poses a major health risk (Boyd et al. 2012). Symptoms of mild hypothermia may include mental confusion, tachycardia, a fast respiratory rate, high blood pressure and shivering (McCullough et al. 2004, Hanania et al. 1999). Moderate and severe hypothermia include symptoms such as oliguria, ventricular arrhythmia, amnesia, slurred speech, a decrease in heart rate (HR), breathing rate and blood pressure as well as coma (Petrone et al. 2014, Brown et al. 2012).

There is no good definition for cold water. However, because many of the hazardous responses to cold water appear to peak on immersion somewhere between 15 and 10°C it is reasonable to say that cold water is water <15°C (Tipton et al. 1991). A thermoneutral temperature with the head out of the water is 34.5°C (Boussuges 2006)—temperatures as warm as this are almost never present when diving. For this reason, even in warm diving locations, thermal protection, for example wetsuits, are mostly used. The mean skin temperature (Tskin) is usually around 32°C, and a drop of Tskin to 28°C causes a significant thermal loss and rapidly decreased cognitive and physical performance for the immersed person (Gerth et al. 2007). Manual dexterity deteriorates significantly when the hand skin temperature decreases to 15°C (Chen et al. 2010), and higher pressure seems to speed up impairment in dexterity (Zander et al. 2008).

If an unprotected diver is immersed in cold water four phases are observed (Pollock 2014): 1. *Cold shock* develops within the first two minutes and, in this phase, the respiratory rate and heart rate increase whereas the cerebral blood flow decreases due to decreased carbon dioxide levels in the blood caused by hyperventilation; 2. *Swimming failure* is caused by the weakening of the chilled skeletal muscles and is likely to cause the drowning of unprotected swimmers if the first phase is survived; 3. *Onset of hypothermia* occurs as the deep body temperature falls below 35°C; and 4. *A critical phase* is the time when victims are rescued from cold water. Handling stress, loss of hydrostatic pressure due to removal from water combined with an increase in circulatory demands can cause a circulatory collapse (Golden et al. 1991). Additionally, after exposure to cold a so-called "after drop" in deep-body temperature occurs if the skin is warmed. This "after drop" is caused by increased blood flow in the skin and periphery and must be taken into account when rescuing hypothermic victims. An "after drop" occurs also after regular cold dives (Pollock 2007) but has seldom any greater relevance.

Divers dive throughout the year and in all locations of the planet (Pollock 2007, Buzzacott et al. 2018). In colder places, as in the Arctic, water temperatures can be lower than the freezing point under surface ice. The maximal density of fresh water is at 4°C (Ruth et al. 2010), which causes water at this temperature to build up at the bottom of seas and lakes. In Arctic places, even in warmest summer, water temperatures will be 4°C at a depth of 20 meters and deeper. Even in warmer locations water temperatures get closer to 4°C when diving deep enough.

2.2 Decompression illness (DCI)

Decompression illness (DCI) is a condition caused by inert gas bubbles formed during ascent from an overpressure environment. Intravascular and extravascular inert gas bubbles may cause a variety of symptoms depending on where the bubbles form and where they migrate. DCI comprises two subcategories with different etiologies: the more common condition called decompression sickness (DCS) and the more serious condition arterial gas embolism (AGE) (Mitchell et al. 2019).

DCI is one of the most common diving related disease (Buzzacott et al. 2018). While the reported incidence of DCS (occurrence per dive), depending on the diving population, varies from 0.015% to 0.095% (Vann 2004, Ladd et al 2002), with the occurrence of symptoms associated with possible AGE being only 3.9% of all DCI cases according to data from the Divers Alert Network (Pollock 2008).

2.2.1 Etiology and pathophysiology

During diving the human body is exposed to an overpressure environment. Normal breathing air consists of 21% oxygen and 79% nitrogen (Skorucak 2018). Oxygen is vital for aerobic energy production in mammal cells and is therefore vital to humans (Schmidt-Rohr 2020). Nitrogen is an inert gas that gives volume to the gas mixture and it is not needed for cell breathing. Nitrogen can easily be changed to another gas without impairing the cell function. This is done for example in technical diving, where helium is a commonly used inert gas.

In a normobaric atmospheric pressure (101 kPa = 1 bar) the nitrogen partial pressure is 0.8 bar. When the pressure rises, the volume of the gas mixture decreases according to Boyle's law (Boyle 1662). According to Dalton's law the pressure of a gas is the sum of the partial pressures of all gases in the mixture, thus the partial pressure of all the gases in the mixture increase (Dalton 1802). This means that for example at a depth of 20 msw/mfw the pressure of breathing air is 3 bar and the partial pressure of nitrogen is 2.4 bar. According to Henry's law the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid (Henry 1803), meaning that with an elevated nitrogen partial pressure in the lungs also more nitrogen is dissolved in the body while diving. The same law applies also to other gases.

In other words, breathing gas at an elevated pressure causes more gas to dissolve into the blood and tissues. Tissues with an active metabolism and good blood circulation are usually referred as "fast tissues". These fast tissues are rapidly saturated with inert gas during diving, but they also release inert gas quickly when the pressure is reduced. "Slow tissues" have less blood circulation or lack circulation and usually have a less active metabolism. For slow tissues it takes longer to reach the inert gas saturation limit, and for these tissues it also takes longer to release inert gas (Bühlmann 1984).

When a diver returns to the surface the ambient pressure decreases. This leads to a decrease of the partial pressures of the gases in the lungs. According to Henry's law now inert gas is then released from saturated tissues and transported with the blood circulation to the lungs. If the ascent is too fast and the tissues have been saturated to a sufficiently high degree, the tissues become supersaturated, meaning the gas partial pressure exceeds that of the gas partial pressure of the lungs. If inert gas cannot be released rapidly enough into the venous blood stream and the lungs (usually the case with slow tissues) bubbles start to form. These bubbles are the cause of DCS. Bubbles can cause mechanical damage in the tissues and stroke-like symptoms due to vascular obstruction. Secondary effects of bubble formation can be endothelial damage, hemoconcentration, platelet activation and decreased effects of vasoactive compounds (Boussuges et al. 1996, Nossum et al. 2002, Brunner et al. 1964, Bosco et al. 2001).

In recent years, the role of endothelial dysfunction in DCS has been of special interest in research since studies have shown a correlation between DCS and biomarkers for vascular permeability (Gempp et al. 2014, Zhang et al. 2016). Especially neurological DCS has been linked to endothelial dysfunction (Barak et al. 2020). Because of these findings there has been great interest in finding ways to influence the endothelial function in divers (Theunissen et al. 2013). Studies have shown an impaired endothelial function even after dives not resulting in DCS (Mazur et al. 2014), which supports the idea that diving influences the endothelium, and lends weight to the hypothesis of a central role of endothelial dysfunction in DCS (Madden et al. 2009). Other studies show that endothelial dysfunction is not solely related to venous gas emboli (Germonpré et al. 2017), therefore this subject still requires more research.

The usually more fatal of the two subcategories of DCI is an arterial gas embolism (AGE) (Lippmann et al. 2013). In contrary to DCS, AGE is not caused by inert gas dissolved in the tissues. According to Boyle's law, the volume of gas increases while ambient pressure decreases. If a diver breathes air from a regulator at a depth of 10 msw/mfw and ascends quickly to the surface with a lung gas volume of 5 liters without breathing out, the surface lung volume would theoretically be 10 liters. Surfacing quickly as described without breathing out sufficiently can cause lung damage. AGE is caused by lung rupture and gas entering the arterial circulation causing obstruction and stroke-like symptoms. If gas migrates to the central nervous system or to blood vessels supplying the heart, this can have fatal consequences. AGE might occur from depths as shallow as 1-1.5 meters (Benton et al. 1996, Hampson et al. 2020).

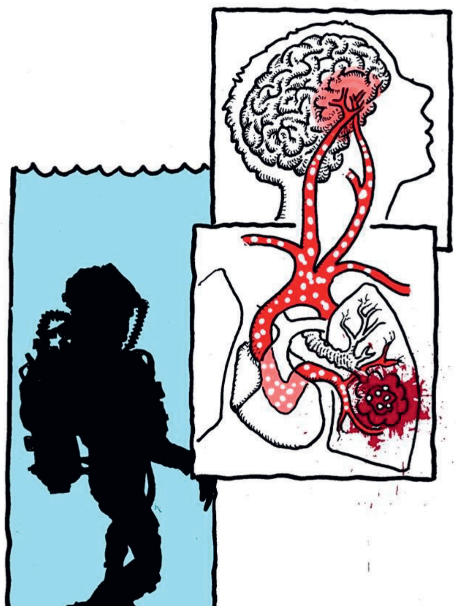


Figure 1: Arterial gas embolism is caused by the arterialization of alveolar breathing gas due to lung rupture. This can be caused for example by ascending to quickly while holding the breath.

AGE and DCS may also be present at the same time. Because of this and because it is seldom of clinical relevance to distinguish between these two, while the treatment is the same for both, the term DCI is recommended in clinical use by most international diving medical organizations (Mitchell 2019). Albeit AGE and DCS can be present at same time, the use of the term “AGE” for venous inert gas bubbles that have arterialized through patent foramen ovale (PFO) and/or lung shunts is discouraged by the same international organizations (Mitchell 2019).

2.2.2 Risk factors

The risk of DCS is increased with prolonged diving time and depth, and with factors that affect the tissue inert gas saturation and release of gas from tissues during ascent. A common cause for DCS is an overly rapid ascent. For longer and deeper exposures special decompression schedules “diving tables” were suggested more than 100 years ago. The first decompression models were published in 1908 by professor J. S. Haldane, who did large-scale research on goats in compression chambers. Goats were compressed to various depths and observed for possible symptoms and signs of DCS as the pressure was decreased at different speeds. Based on these clinical trials Haldane developed a five-tissue compartment model with half times of 5, 10, 20, 40 and 75 minutes in which decompression stops were set near a theoretical tissue super saturation line, a limit where according to his research symptoms began to occur to an increasing extent (Boycott et al. 1908).

The Haldanian model was further developed by Dr. A. Bühlmann who published a 16-tissue compartment model with the same principles in 1983 (Bühlmann 1984). In diving medicine Haldane’s and Bühlmann’s decompression models are referred as gas content models in contrast to newer so-called bubble models, for example the Varying Permeability Model (VMP) and the Reduced Gradient Bubble Model (RGBM), where the idea is to make the decompression stops near the saturation line and by this avoid the formation of bubbles (Imbert et al. 2004). Bubble models are in fact mathematical models and no human research exists to prove if these would form less bubbles than the traditional gas content models. One study by the Navy Experimental Dive Unit has even proven the contrary (Doolette et al. 2011). Many divers nowadays use gas content models with so-called gradient factors (GFs), that constitute the amount of supersaturation that the diver is willing to gain during decompression (Anttila 2012). This means that gas content models are modified to look more like bubble models—in other words these are a compromise between the two models.

Figure 2: Professor J. S. Haldane published his decompression model with five-tissue compartments in the Journal of Hygiene in 1908 (Boycott et al. 1908). Figure and text from the article "The Prevention of Compressed-air Illness". Re-published with the permission of Cambridge University Press.

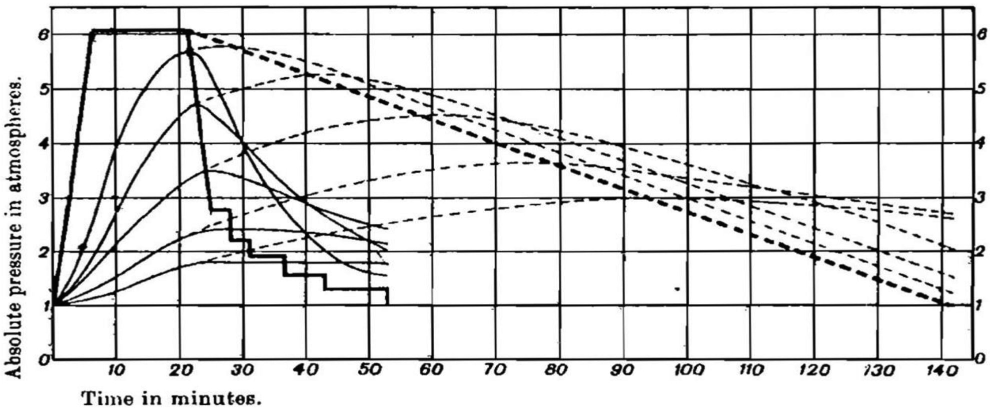


Fig. 4. Desaturation during stage decompression in 32 minutes and uniform decompression in 2 hours, after exposure for 15 minutes at 75 lbs. pressure with compression in 6 minutes. Thick lines = air pressure: continuous lines = stage decompression: dotted lines = uniform decompression. The curves from above downwards represent respectively the variations in saturation with nitrogen of parts of the body which half saturate in 5, 10, 20, 40, and 75 minutes.

Figure 3: From Professor J. S. Haldane's same article as above: `"Bends" of fore-leg in a goat.´ Haldane did the majority of his research on decompression theory on goats that he compressed in a hyperbaric chamber. Re-published with the permission of Cambridge University Press.

In addition to time and depth as well as decompression related issues, many other factors have been associated with an increased risk of DCS. These are described below.

Exercise and psychological stress, which increases the breathing rate and gas consumption during diving elevates the risk of DCS (Vann 2004). An increase in gas consumption causes more inert gas to dissolve into the tissues. There are some indications from human studies that exercise before diving could reduce the risk of bubble formation and the risk of DCS (Blatteau et al. 2005 and 2006, Dujic et al. 2004). On the other hand, exercise after diving opens the peripheral blood circulation which causes a fast release of inert gas from the tissues and bubbles can form (Jankowski et al. 2004, Madden et al. 2016). This in turn increases the risk of DCS. Moreover, it has been demonstrated that lung shunts, which enable the arterialization of bubbles, may open during exercise (Lovering et al. 2007). For these reasons, exercise should be avoided after diving.

Temperature has a major impact on the risk of DCS. If the diver is warm at the beginning and bottom phase of the dive, the peripheral blood circulation is wide open, and a lot of inert gas is dissolved into the tissues. If the diver then gets cold during ascent, inert gas cannot exit tissues effectively because of vasoconstriction. This afore described situation where the tissues first load a lot of inert gas and then cannot expel it as the ambient pressure decreases obviously illustrates an increased risk of DCS (Gerth et al. 2007). To minimize the temperature-related effects of DCS the diver should be lightly cold at the beginning and bottom phase of the dive and comfortably warm during decompression. This would lessen the amount inert gas dissolved into the tissues and allow it to leave the tissues during ascent. The effects of cold should be taken into account especially when diving in very cold conditions (Gerth et al. 2007).

The role of a PFO and other atrial defects have long been debated. There are studies that support their role in an increased risk of neurological and cardiopulmonary DCS and skin symptoms (cutis marmorata), especially if the PFO is large in size (Moon et al. 1989, Germonpre et al. 1998, Wilmhurst 1990). The size of the PFO seems to be of great relevance—with the median atrial defect being 10 mm in divers who had experienced DCI, which is significantly higher than the general population (Wilmhurst et al.2015). Venous inert gas bubbles can arterialize through a PFO or septal wall defect and migrate from inert gas saturated tissues and cause DCS symptoms (Mitchell et al. 2009). However, PFO screening for divers is not recommended on a routine basis because 25-28% of adults have a PFO, and most divers, also those who have a PFO, never get DCS (Torti et al. 2004).

Figure 4: A large patent foramen ovale (PFO) is considered to cause an elevated risk of neurological and cardiopulmonary DCS. It allows venous inert gas bubbles to migrate to the arterial side. To the left a heart without a PFO. To the right a heart with PFO, that allows inert gas bubbles to enter the arterial circulation.

If a diver repeatedly gets milder DCS or experiences once severe neurological DCS, it could be useful to examine if the diver has a large PFO. The South Pacific Underwater Medicine Society has made a joint position statement on PFO screening for divers (Smart et al. 2015). In this position the authors recommend screening for high risk divers, such as those with a history of spinal, inner-ear or cutaneous DCI, migraines with auras, a family history of PFOs or atrial septal defects and those with other forms of congenital heart disease. If a large PFO is discovered and the diver is still highly motivated to continue diving and is not willing to change diving practices (often technical divers and occupational divers) a procedure where the PFO is closed can be considered. Closing the PFO seems to significantly reduce the risk of neurological DCS (Billinger er al. 2011). Another passage for possible arterialization of inert venous gas bubbles are lung shunts that normally open during changes in lung pressure and physical stress (Lovering et al. 2007). Through lung shunts arterialized bubbles cause similar symptoms than those which have arterialized through PFO or atrial septal defects.

There seems to be a slight increase in the risk of DCS with age and BMI (Dunford et al. 2002, Vann 2004). Dehydration has been associated with an increased risk in animal studies (Wang et al. 2020) and there is limited data that supports this from human studies (Gempp et al. 2009).

Multiple dives per day are associated with a higher the risk, as this causes inert gas to build up in tissues from consecutive dives (Cialoni et al. 2015). Multiple day diving has also been associated with an increased risk, but some studies actually indicate the opposite, possibly due to acclimatization (Zanchi et al. 2014). Acclimatization could produce a reduction in the biochemical response—mainly that of nitric oxide, effectively leading to a desensitization to decompression stress. Flying after diving increases the risk because of a decrease in the ambient pressure and is therefore not recommended directly after diving (Sheffield 1990).

One way to reduce the toxic effects of nitrogen on the central nervous system (CNS), known as nitrogen narcosis, and the retention of nitrogen in the tissues is to reduce the amount of nitrogen in the breathing gas. Widely used examples where this is done are oxygen enriched gas mixtures, often called Nitrox or EAN (= Enriched Air Nitrox) in diving. These are useful but sometimes give a false sense of safety, and some divers do not follow depth and time recommendations, as they are overly convinced of the superior features of these gas mixtures.

AGE is a result of intra-alveolar gas entering the arterial circulation due to lung rupture (Walker et al. 2020). All causes that elevate the risk of lung rupture in an environment of pressure change are risk factors for AGE. Lung diseases that cause weakness in the lung tissue, for example pneumonia, some other inflammatory diseases as well as scar tissue, structural impairment of the lung tissue and earlier spontaneous pneumothorax are potential risk factors. Additionally, conditions that can cause air trapping in the lungs, for example asthma, pulmonary cysts, blebs, and bullae increase the risk (Weiss et al. 1995, Mellem et al. 1990).

2.2.3 Symptoms

There are a wide range of DCI symptoms, extending from mild to serious and even fatal manifestations depending on where bubbles form and migrate. AGE normally has a rapid onset, with the symptoms emerging directly when the diver surfaces. AGE is statistically the most fatal form of DCI and often has serious neurological stroke-like and cardiopulmonary manifestations (Nijk et al. 2017, Casadesús et al. 2018). DCS symptoms often form more slowly. According to a study on naval divers 42% of subjects who had DCS experienced symptoms within one hour after surfacing, 60% within three hours, 83% within eight hours and 98% within 24 hours (U.S. Navy Supervisor of Diving 2008). Late symptom onset is often connected to secondary DCS changes and tissue injury.

DCS is traditionally divided into type 1 and type 2 DCS based on the symptoms (Golding et al. 1960). Type 1 DCS comprises symptoms such as musculoskeletal and joint pain, skin manifestations such as swelling or rash (cutis marmorata), fatigue, and nausea. Type 2 DCS includes neurological symptoms such as paresthesia, numbness, tingling, muscle weakness, paralysis, and motor abnormalities, as well as cardiopulmonary symptoms (Francis et al. 2003).

Later another more descriptive way of classifying DCS has recently been proposed: in this model the type of symptoms and their evolvement is described, for example as “developing central nervous system DCS with hemiplegic manifestations” or “declining neurological DCS with itching and tingling on left upper extremity”. Compared to the older classification method, this method may be better in clinical use because the older method does not necessarily determine the severity of the disease. For example, DCS with relatively mild neurological symptoms is automatically classified as DCS type 2, whereas severe articular joint pain is automatically classified as type 1 DCS. Additionally, for example a special type of DCS manifestation, a skin rash “cutis marmorata” (type 1 DCS), is associated with the development of more severe neurological and cardiopulmonary DCS symptoms (Francis et al. 1991).

2.2.4 Differential diagnosis

There are several medical conditions whose clinical manifestations may resemble those of DCI. It is vital not to miss medical conditions that need acute, specific treatment or that possibly worsen during HBOT.

Table 1: Medical conditions that may resemble DCI.

Medical condition	Resemlance with DCI symptoms
Musculoskeletal trauma or strain	pain of joints and extremities are usual manifestations of DCI
Immersion pulmonary oedema	cardiorespiratori DCI
Water aspiration	cardiorespiratori DCI
Angina pectoris and other heart conditions	cardiorespiratori DCI
Acute neurtological disorder	central nervous system DCI
Inner-ear barotrauma	inner-ear DCI
Overinflation of gas-filled cavities of the upper respiratory tract	pain resembling DCI symptoms
Food poisoning	head ache, tiredness, confusion and constitutional symptoms are usual in DCI
Dehydration	same as above
Psychological disorder	same as above
Breathing gas related effects	same as above
Non-freezing cold injury	pain of joints and extremities are usual manifestations of DCI

Sometimes it can be hard to differentiate between varying causes of symptoms. Additionally, the possibility of several underlying conditions should not be forgotten. Especially, if the diver experiences symptoms during diving, he or she may possibly ascend to the surface quickly also getting DCI, while the primary cause of the symptoms was due to some other condition.

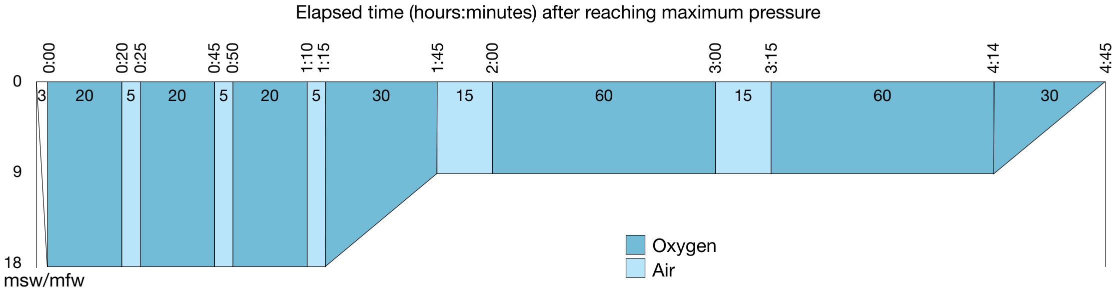
2.2.5 Treatment

If the patient is severely ill, maintenance of basic organ functions is vital. More specific first aid treatment for DCI is to breathe 100% oxygen (Hyldegaard et al. 1991, Longphre 2007). If possible, this should be continued until the patient is evaluated by a physician who confirms the diagnosis and determines further treatment. Moreover, hydration especially in severe cases, should be included in first aid treatment (Moon 2003). Fluids can be given intravenously, but for stabile, conscious patients per oral fluids may be considered. Fluids should preferably be isotonic (Moon 2003).

The gold standard treatment for DCI is recompression in a hyperbaric chamber while breathing 100% oxygen (Vann et al. 2011). Delays in recompression treatment should be avoided because bubbles may cause severe symptoms and because of the secondary changes that normally form hours after the onset of symptoms if not treated (Steigleman et al. 2003). Hyperbaric oxygen therapy (HBOT) reduces the size of inert gas bubbles and makes them dissolve and increases the partial pressure difference of the inert gas between the lung and tissue, which makes the inert gas exit the tissues more rapidly. Normobaric oxygen has partly same effects and is therefore recommended as first aid. HBOT also improves tissue oxygenation in possibly hypoxic tissues, lessens swelling through vasoconstriction and diminishes inflammatory responses that aggravate tissue damage (Martin et al. 2002).

The most commonly used HBOT treatment schedule for the first treatment of DCI is USN TT6 and its modifications. This treatment is 4 hours and 50 minutes long and the main treatment pressure is at 2.8 bar, which corresponds to a depth of 18 msw/mfw (U.S. Navy Department 1975). HBOT treatment can be repeated several times until symptoms reach a clinical plateau. Re-treatment protocols differ a lot depending on local instructions. Often re-treatment HBOT is done with shorter or shallower protocols, such as the USN TT 5 or 9 (Haas et al. 2014, Bennett al. 2012). The reason why most clinics utilize the longer USN TT6 only for re-treatment of severe neurological residual symptoms is the elevated risk of CNS and pulmonary oxygen toxicity with repeated, long, deep, treatment protocols (Donald 1947, Thorsen et al. 1998).

Figure 5: In Finland the U. S. Navy Treatment Table 6 is the most frequently used treatment protocol for decompression sickness. The maximal treatment pressure equals 18 msw/mfw. The total treatment time is about 4 h 50 min.



Patients should be assessed after HBOT and the risk of the recurrence of symptoms should be taken into account when planning possible re-treatment and follow up. After DCI treatment with HBOT many organizations recommend not to dive for 7–60 days depending on the severity of the symptoms (Vann et al. 2011). Ideally patients should be evaluated by a trained diving physician before they continue diving after treatment.

Even if HBOT for DCI in humans lacks large double-blinded-controlled trials, there is a strong consensus among specialists in the field that the treatment is effective (Moon et al. 1998). Current recommendations include treatment of even very mild symptoms with HBOT, even if breathing 100% normobaric oxygen also seems to give good results in these patients (Mitchell et al. 2018).

Some divers use so-called in-water-recompression (IWR) which is not recommended as first line treatment because of its inherent risks (Mitchell et al. 2018, Doolette et al. 2018). Breathing 100% oxygen under water may cause a convulsion and possible drowning due to CNS oxygen toxicity effects. Due to not well understood neuromodulatory effects, CNS oxygen toxicity seems to appear at a lower oxygen partial pressure in water than in a pressurized chamber (Donald 1992). In diving, the oxygen partial pressure limit is normally set to 1.7 bar, equaling 7 msw/mfw. Most IWR protocols include breathing 100% oxygen at 9 msw/mfw or even deeper.

A group of internationally known specialists in the field of diving medicine have suggested guidelines for IWR (Mitchell et al. 2018). If it is not possible to get to a chamber, for example in remote locations, IWR can be considered for mild DCI symptoms. The diver should be fully conscious and orientated and should not experience any cardiopulmonary symptoms. If possible, the diver should have a full faced mask and be assisted by another diver for the whole treatment. Some widely used IWR methods are the “Australian method”, the US Navy In-water recompression tables and the Clipperton in-water recompression table.

2.2.6 Prognosis

Most DCI patients recover well after HBOT. In earlier studies 45–78% of patients were completely asymptomatic at hospital discharge (Svendsen et al. 2016, Kot et al. 2008, Gempp et al. 2010, Blatteau et al. 2011, Aharon-Peretz et al. 1993). The majority of residual symptoms were mild in these studies. The most frequent residual symptom after DCI is mild paresthesia (Vann et al. 2000). There are strong indications that a delay in HBOT worsens the outcome of the treatment, hence delays starting HBOT should be avoided. In a study with experimental dives where HBOT was immediately at hand 97% of DCI cases became totally asymptomatic after the first treatment and all were asymptomatic after successive HBOT (Thalmann 1996), even if this group included serious cases of DCI.

The worst clinical outcomes and the highest fatality rate are seen in the AGE group. There are no good statistics on outcome of treatment of AGE in divers. However, according to case reports, patients with confirmed AGE have a high fatality rate (Nijk et al. 2017, Casadesús et al. 2019, Trytko et al. 2008).

2.3 Thermal protection in diving

Heat energy is lost due to thermal conduction, convection, radiation, and evaporation (Kurz 2008). The heat capacity of the environment plays an important role in how quickly body heat is lost. The heat capacity of water is higher than that of air (Mallamace et al. 2020, Wang et al. 2020), which causes a more rapid heat loss when immersed.

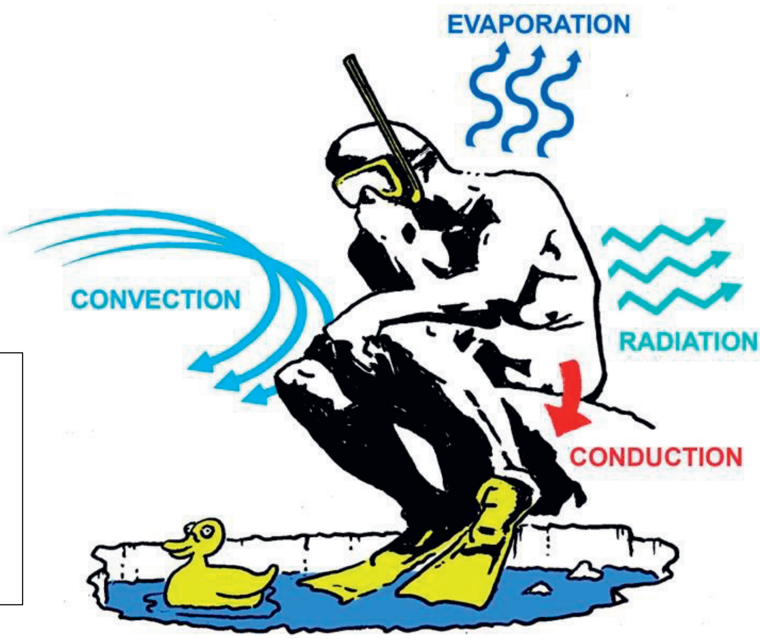


Figure 6: The human body loses heat energy via thermal conduction, convection, radiation, and evaporation.

The diver loses heat via the surface of the body and via the lungs while breathing. The thermoregulatory mechanisms, controlled by the ANS, act to maintain the body's desired temperature when exposed to temperatures below thermoneutral values (Collins 1999). Thermoregulatory changes include skin vasoconstriction and centralization of blood circulation, increase in metabolic rate, heat production from brown adipose tissue and increase in HR as well as shivering (Young et al. 1996). If heat production is not able to compensate for heat loss, eventually the body core temperature decreases.

2.3.1 Suggested thermal protection methods

Different methods have been developed to protect the diver from cold. In warmer locations wetsuits are often used. Wetsuits allow in water that is warmed up by the body. As the water in the suit does not change too fast, heat loss through convection is reduced. Two hours of diving with 2-3 mm wet suit in 16 to 20°C water in laboratory conditions has been found not to cause a drop in core or skin temperatures to critical levels, but the time for managing a series of cognitive, manual dexterity, and muscle strength tests was found to increase significantly, suggesting that cognitive and physical performance is impaired in these temperatures (Dror et al. 2019). Another study on wet suit divers in the Antarctic showed that dives with a median duration of 29 minutes caused a median decrease of the skin temperature to 29°C and a median heat loss of 850 kJ. Core temperatures below 36°C were not recorded in that study. Although, the divers in the study did not become hypothermic, their skin temperatures in their extremities decreased to levels that influence dexterity and physical performance (median temperature of hand: 10°C) (Bridgman 1990). A third study on wet suit divers showed that wet suit insulating properties decrease with increased exercise. This could be explained by cold water entering the suit while moving, which in turn would cause more convection of heat (Yeon et al. 1985).

If better heat protection is needed drysuits are usually preferred. When these are used in cold water conditions heat loss can be diminished in many different ways—therefore the heat loss varies a lot depending on factors such as the water temperature, diving gear and devices, as well as diver heat production, and personal properties. Drysuits enable the use of additional layers and active warming devices. Warming devices, such as vests, heat producing gloves and other special warming garments can be useful but are not problem free. They are subjectable to malfunction, can cause local skin burns, and can increase the risk of DCI if used incorrectly (O'Connor et al. 2009). Drysuits work only if their outer layer is kept away from the skin. When the ambient pressure increases as the diver descends, the suit has to be inflated successfully to avoid this. Special drysuit undergarments and trapped gas materials have been developed to avoid a suit squeeze and to maintain a good insulating gas layer in the suit. Additionally, different insulating gases may be used in drysuit diving, and these may influence heat loss. Many technical divers prefer argon as a drysuit inflation gas because of its lower heat conductivity compared to air.

On very deep and long dives, such as occupational saturation diving, sometimes special warm water suits are used. In these, circulating warm water is pumped into the suit to keep the diver warm. Additionally, the breathing air can be warmed to reduce heat loss. Although, recreational divers seldom pay much attention to this, the breathing gas may actually influence heat loss significantly. For example, technical divers use a lot of helium containing breathing gas mixtures. The thermal properties of helium lead to a greater amount of heat loss through breathing compared to air (heat conductivity of helium: 151 mW · $m^{-1}K^{-1}$ vs. air: 25.9 mW · $m^{-1}K^{-1}$). However, if a rebreather is used, heat loss through breathing is compensated for somewhat by the device that recycles the same, already heated gas to which O_2 is added and CO_2 removed.

2.3.2 Argon used as a drysuit insulation gas

Many divers use argon as a drysuit inflating gas. Especially in colder conditions argon is preferred by many. The technical diving community, who dive all year round, on deep and long dives, often with helium containing breathing gas mixtures (Trimix or Heliox), are active users of argon. In theory, the thermal protective properties of argon are better than air, because of its 31% lower heat conductivity (argon: 17.72 mW·$m^{-1}K^{-1}$ vs. air: 25.9 mW·$m^{-1}K^{-1}$) (Nucklos et al. 2008). Although, not much scientific data is at hand to support the superiority of argon, many divers are convinced argon users.

Two previous studies have been done on human subjects to compare argon and air used as a suit inflation gas in drysuit dives (Risberg et al. 2001, Vrijdag et al. 2013). These studies did not show a difference between the groups. However, the research groups were small in these studies. The first study included six dives for both groups (argon and air), and the second study involved 13 dives with argon vs. six dives with air. Additionally, the study settings had many limitations, so the superiority of argon remains a much-debated subject. For example, in one of the studies the only objective measured variable was body core temperature (Vrijdag et al. 2013). Actually, the colder the diver gets, the higher core temperature gets due to centralization of blood to vital organs and due to the body's increased heat production of the body (Hayward et al. 1975). For this reason, the core temperature is not an optimal measure for evaluating thermal loss in divers. In the other study both core and surface temperatures were measured (Risberg et al. 2001). As discussed in this study, the horizontal position of divers and lack of thick clothing layers under a drysuit leads to the suit pressing against the divers' body parts facing down. This might have influenced the outcome of the study. If the gas is not where it should be to keep the diver warm, its properties loose relevance.

In addition to these studies, a comparison of argon and air has been done on heated mannikins in laboratory conditions (Nucklos et al. 2008). Heat loss was evaluated by measuring the electrical power levels needed to maintain a fixed mannikin surface temperature of 30°C. This comparison showed a difference between groups in favor of argon, but this does not prove that the conclusions could necessarily be transferred to humans.

2.4 The human diving responses

Human diving responses, sometimes called the "diving reflex", are a group of different physiological changes that occur when a diver submerges under water (Lindholm et al. 2008). These changes help the body to adapt to underwater conditions, most importantly to conserve oxygen (Panneton 2013). A decreased oxygen consumption improves the survival time under water.

Factors that increase the diving responses in humans are facial sensation of wetness and cold, breath holding, submersion, a cold environment, and increased acidity of the blood (Lundgren et al. 1985, Butler et al. 1997).

2.4.1 Diving responses in mammals

In 1870, the physiologist Paul Bert described a significant slowing in the HR of submerged ducks (Godek et al. 2020). Many aquatic mammals, such as seals and dolphins have strong diving responses that enable long times of submersion. In addition to a slowed HR, they have an elastic aorta and a large storage capacity in the veins of the lungs, which are important for maintaining the blood pressure with a low HR and for long periods of submersion (Panneton 2013). Additionally, a large blood volume and a high level of hematocrit, hemoglobin, and myoglobin act as oxygen storage during submersion. Brain tissues in aquatic mammals also have high levels of cytoglobin and neuroglobin (Panneton 2013).

2.4.2 Mechanisms in humans

The diving responses change from childhood to adulthood. Infants have a strong laryngeal chemoreflex, that on the sensation of fluid in the airways, causes swallowing and apnea (Xia et al. 2013). This reflex protects the lower airways during immersion and enables baby swimming, for example. When growing up the strength of this reflex decreases, and in adults a similar laryngeal irritation primarily causes coughing (Bradley 2007).

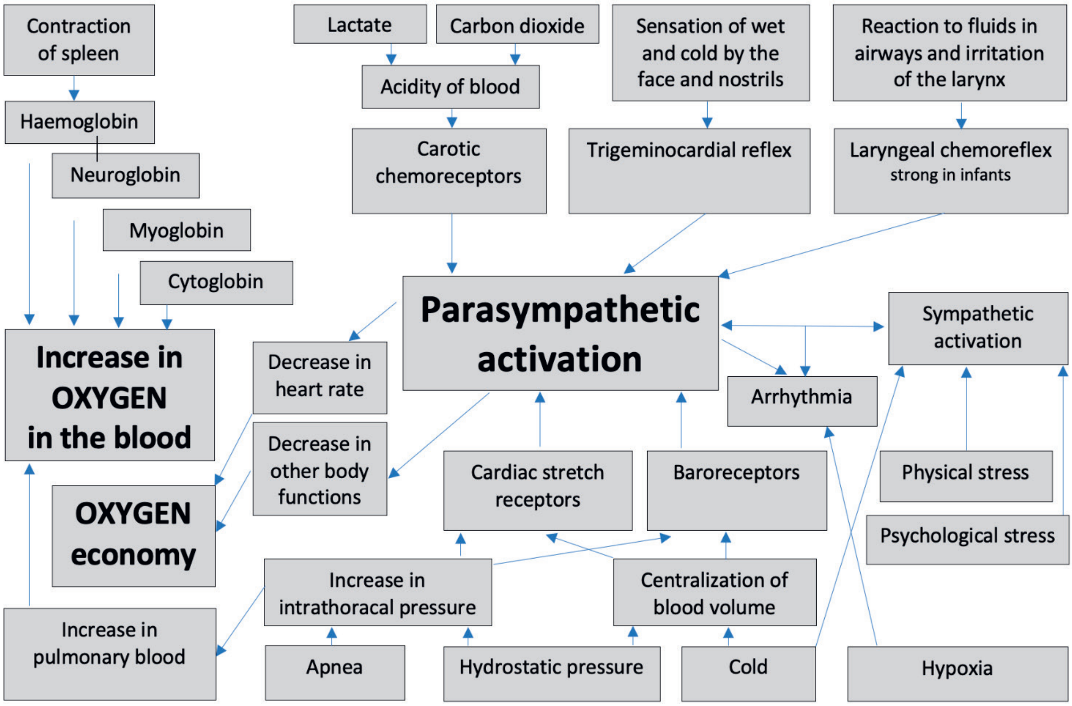
Other diving responses are still present in adults. The trigeminocardiac reflex causes parasympathetic output to the heart which slows HR and cardiac output due to the sensation of cold and wet on the face and the nostrils (Speck et al. 1978). When divers hold their breath, as they do in freediving, blood CO_2-levels and the amount of lactate rise and carotic chemoreseptors sense a rise in acidity, which in turn causes parasympathetic activation and a lowered HR (Lemaître et al. 2008). Apnea after inspiration also increases the intrathoracic pressure which activates baroreceptors and cardiac stretch receptors which also cause parasympathetic activation (Taboni et al. 2020, Hakumäki 1987).

Moreover, hydrostatic pressure causes blood to move away from the periphery due to the increased pressure on the tissues and to be centralized, which in turn causes an increase in the central blood pressure. This in turn causes the activation of carotid baroreceptors and cardiac stretch receptors, which leads to parasympathetic activation and reduced HR and cardiac output (Armstrong et al. 2020). Cold has the same effects as that of the hydrostatic pressure, therefore diving responses are normally stronger when one is exposed to cold water (Young et al. 1996).

Other changes that can be counted as part of the human diving reflex are contraction of the spleen, which causes an extended amount of red blood cells to enter the circulation (Lindholm et al. 2009). This enables vital organs to take even these oxygen stores into use. In freediving as the diver descends, the volume of lung air decreases due to the ambient pressure. This causes an increased amount of blood to enter the lungs, which enables more effective oxygenation of the hemoglobin of the blood from the decreasing amount of oxygen in the alveoli (Schagatay 2014). Additionally, oxygen from myoglobin, cytoglobin and neuroglobin is utilized during hypoxia in freediving.

Because of the strong parasympathetic output to the heart, especially during breath hold diving, the risk of arrhythmia is increased (Lindholm et al. 2009). Electrocardiogram (ECG) recordings of freedivers often show frequent ectopic beats, as well as ECG changes such as ST changes, heightened T and U waves, that indicate a reduced left ventricular function and overall decrease in cardiac function and a hypoxic state (Lindholm et al. 2009). With concurrent sympathetic activation, for example due to the first sensation of cold when entering the water or physical or phycological stress during the dive, the risk of arrhythmia is even higher. Concurrent parasympathetic and sympathetic activation have been associated with malign arrhythmia (Buchholz et al. 2017, Kane et al. 2018).

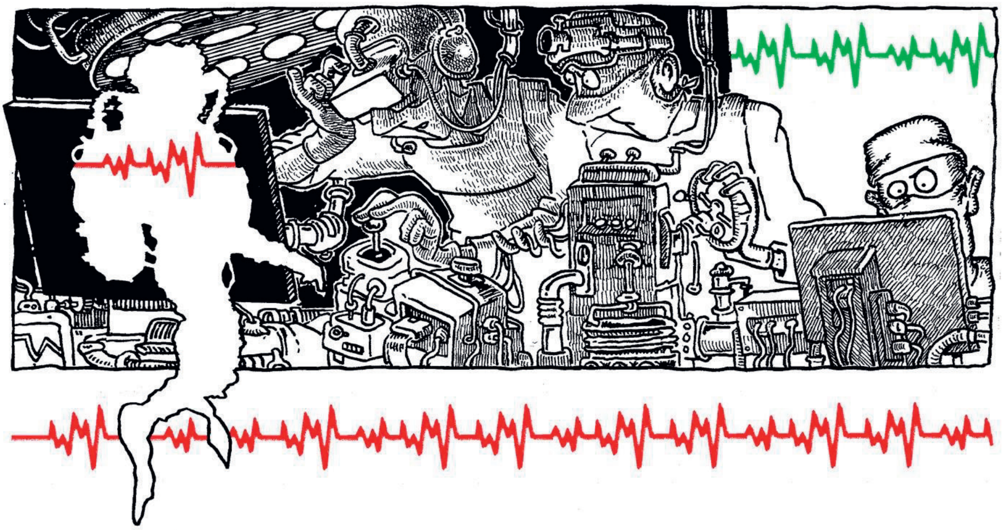
Figure 7: The human diving responses—factors influencing oxygen consumption and survival time under water, and other physiological responses to diving.



2.5 Heart rate variability (HRV)

The HR is the number of heart beats of the heart per minute. Heart rate variability (HRV) is the variation in time intervals between heartbeats (McCraty et al. 2015). A healthy heart does not function as a metronome—beat-to-beat intervals variate due to a complex brain to heart function that is regulated by the ANS (Goldberger 1991). The ANS can be divided into the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS). The SNS is predominant when humans are exposed to physiologically or psychologically stressful situations, sometimes referred to as "fight or flight" responses. The PNS is in predominant when resting. The PNS slows the HR and a strong PNS stimulus can even stop the heart for a while (Tortora et al. 2017).

Figure 8: Heart rate variability (HRV) can be analyzed from ECG recordings. For the moment, HRV studies are still rare in diving medicine research.



2.5.1 HRV metrics and norms

Mechanisms that generate data for different length measures of HRV have been studied. Most used measures are for 24 hours, short term (usually about 5 minutes), and ultra-short term (shorter than 5 minutes) in length. Three metrics are widely used to analyze HRV recordings: the time-domain, the frequency-domain, and non-linear metrics (Shaffer et al. 2017). Time-domain metrics report the amount of HRV observed during a recording. Frequency-domain values are calculated from the absolute or relative signal energy in recordings. Non-linear measures calibrate the complexity and unpredictability of a series of inter-beat intervals (IBI) (Shaffer et al. 2017).

2.5.2 Factors that influence HRV

Autonomically regulated physiological systems enable quick adaptation to the changing environment. The influences of the ANS on the cardiac sinus node are reflected as changes in the beat-to-beat intervals of the heart (Goldberger 1991). For this reason, HRV measures can be used to examine ANS activity, keeping in mind that the information is gained only from the sinus node function. High HRV does not necessarily mean high parasympathetic activity and a healthy heart. Disease can either increase or decrease HRV (Vaillancourt 2002). Concurrent assessment methods must be used in clinical patient evaluation. For example, in addition to PNS activity, irregular forms of arrhythmia can cause an increase in HRV.

Studies have shown that in addition to the dynamic PNS/SNS function many other phenomena influence HRV.

Short and ultra-short recordings are also influenced by:
1. Respiration via the respiratory sinus arrhythmia (RSA), the respiratory slowing and speeding of the HR via the vagus nerve caused by baroreceptor activity
2. Heart and vascular tone and blood pressure via baroreceptor and cardiac stretch receptor activity
3. The central nervous system
4. The endocrine system
5. Chemoreceptor activity
(Karemaker 2009, R. Gevirtz et al. 2016, Shaffer et al. 2014)

24 hours HRV recordings are influenced more strongly by:
1. Body temperature
2. Metabolism
3. Circadian rhythms
4. The awake-sleep cycle
5. The renin-angiotensin system
(Shaffer et al. 2014)

These longer recordings give better predictive value than short recordings, therefore they are used as a gold standard in the clinical assessment of life expectancy after serious health issues, for example combined with the left ventricular ejection fraction in assessing the risk of cardiovascular death (Shaffer et al. 2014, Kleiger et al. 2005).

Subject dependent factors that influence HRV are:
1. Age, with most HRV measures declining with growing age *(Nunan et al. 2010, Bonnemeier et al. 2003).*
2. Sex (with women showing higher vagal dominance despite a higher mean HR and men with a higher SNS dominance despite lower mean HR) (Koenig et al. 2016).
3. HR (with a higher HR the amount of variation decreases) (McCraty et al. 2015).
4. A high aerobic physical work capacity is associated with higher HRV. Several chronic diseases and medications influence HRV (De Meersman 1993, Bigger et al. 1995).

Table 2: Examples of widely used HRV measures and their interpretation: Mean HR, two time-domain measures (SDNN, RMSSD), and five frequency-domain measures (TP, VLF, LF, HF and LF/HF) with their interpretations.

HR mean	The heart rate is regulated by ANS input to the sinoatrial node. Sympathetic activity increases the heart rate while parasympathetic activity decreases the heart rate (Schmidt-Nielsen 1997).
SDNN	Both sympathetic nervous system and parasympathetic nervous system activity contribute to the SDNN. In short-term recordings, as in this project, the greatest source of the SDNN is the parasympathetically mediated respiratory sinus arrhythmia (Shaffer et al. 2014).
RMSSD	The RMSSD illustrates the variance in the beat to beat heart rate and is the gold standard HRV measure for vagally mediated changes (Shaffer et al. 2014).
TP	The total power is the sum of the power of the ultra-low frequency (ULF), VLF, LF and HF bands (F. Shaffer et al. 2014). An increase in the T power is linked to parasympathetic activity, whereas a decrease is mostly seen as a result of sympathetic activity.
VLF band	The VLF band (0.0033–0.04 Hz) is influenced by many factors. The intrinsic nervous system of the heart seems to contribute (Shaffer et al. 2014). Moreover, physical activity, thermoregulatory, renin-angiotensin, and endothelial influences on the heart contribute to it (Claydon et al. 2008, Akselrod et al. 1981). PNS activity contributes strongly to VLF power (Taylor et al. 1998).
LF band	The LF band (0.04–0.15 Hz) is produced by both the SNS and the PNS (Akselrod et al. 1981, Berntson et al. 2007). It also reflects baroreceptor activity in resting individuals (McCraty et al. 2015), primarily PNS activity via baroreceptors (Reyes del Paso et al. 2013), or baroreflex activity alone (Moak et al. 2007) contributes to LF power. Slow respiration rates, especially when one takes a deep breath or sighs, may through vagal activity contribute to the LF band (Ahmed et al. 1982, Lehrer et al. 2003, Tiller et al. 1996, Brown et al. 1985).
HF band	The HF band (0.15–0.40 Hz), also called the respiratory band, reflects parasympathetic activity, and corresponds to heart rate variations related to the respiratory sinus arrhythmia (Grossman et al. 2007).
LF/HF	Under controlled conditions LF/HF has been used to estimate the relation between the SNS and PNS activity. In fact, as great portions of the LF band power are caused by the PNS and baroreceptor activity and smaller portions by other factors, the use of this ratio is challenged (Pagani et al. 1986, Pagani et al. 1984). Additionally, the SNS contribution to the LF band varies depending on different testing conditions (Shaffer et al. 2014, Kember et al. 2001, Eckberg 1983).

2.5.3 The use of the HRV method in diving medicine and related research

Not many HRV studies have been done in diving medicine. A PubMed search on 16 September 2020 with the terms “diving” and “HRV” produced 19 results. These included original articles and case reports on saturation diving (Hirayanagi et. al 2003), SCUBA diving (Pelzer et al. 1995, Zenske et al. 2019, Schirato et al. 2018, Berry et al. 2017, Zenske et al. 2020, Shipke et al. 2001, Flouris et al. 2009, Lundell et al. 2020), hyperbaric chamber and overpressure facilities experiments (Lund et al. 2000, Lund et al. 2003, Barbosa et al. 2003, Kurita et al. 2002), immersed subjects (Florian et al. 2013), static apnea of breath holding divers (Lemaître et al. 2008), breath holding with the face only in water (Konishi et al. 2016), normal day to day activity of breath holding divers and elite synchronized swimmers (Christoforidi et al. 2011, Solana-Tramunt 2019). One study was on heart transplanted humans, who did a diving test to evaluate ANS function after the operation (Tio et al. 1997).

To our knowledge the first HRV study on divers was published in 1995 by M. Pelzer et al. who studied 25 recreational divers using different HRV measures during the diving, as well as evaluating how much the ECG recording length could be shortened without losing significant information. Their study showed that there was a significant increase in ANS activity during diving compared to control conditions. Moreover, the ECG recording length could be shortened to 3 minutes (time domain measure) and 5 minutes (frequency domain measure) without a significant loss of information compared to longer recording lengths. This study supports the use of short interval HRV in diving medical research (Pelzer et al. 1995).

One HRV study from a hyperbaric environment showed that 100% oxygen increases parasympathetic activity more than air in a chamber with 2.5 bar pressure (Lund et al. 2000). This finding was supported by another study with 13 experienced divers who dived one time with air and one time with EAN40. Both dives increased the PNS activity but diving with EAN40 increased the PNS activity more (Zenske et al. 2019). Another study also from a chamber with 2.5 bar pressure showed strong correlation between SD1 of a Pincaré plot analysis (non-linear measure) and the HF power (frequency domain measure), which supports the idea that SD1 is a good measure also in hyperbaric environments if the HF power cannot be used (Lund et al. 2003).

Other chamber experiments as well as experiments from hyperbaric facilities have shown that the HRV increased and HR decreased as the pressure was elevated (Barbosa et al. 2010). In one study HRV measures before and after a simulated dive in a hyperbaric chamber were compared on two groups breathing the same gases, with one exposed to a hyperbaric environment (557kPa) and the other one acting as a control. The hyperbaric group showed only an increase in the LF power (frequency domain measure) while the controls showed increases in the SDNN (time domain measure), RMSSD (time domain measure), the HF power, and the LF power. This finding was estimated to be related to the physiological stress of being exposed to the hyperbaric environment, and this being reflected in the HRV after the dive (Schirato et al. 2018). In a saturation dive study, an early post dive increase in the HF band was seen indicating PNS activity. A concurrent SNS activity increase was recognized by an increase in plasma epinephrine levels (Hirayanagi et al. 2003). A study from a submarine training facility where subjects were exposed for days to high pressure simulating extreme depth (3445 kPa = 330 msw/mfw) showed an increase in ANS activity and a negative correlation in HF power and urine catecholamines, indicating that extreme depth also influences ANS activity as well as supporting that an increase in stress hormone levels can be seen with the HRV method (Kurita et al. 2002).

Studies on freedivers have shown that experienced freedivers show a biphasic HR decrease during maximal apnea, when controls do not show a second decrease. The second decrease in freedivers happens the same time as PNS activity reflecting an RMSSD increase and a decrease in oxygen saturation occurs. This suggests that the first HR decrease is due to baroreceptors and the second is due to chemoreceptor activity (Lemaître et al. 2008). Additionally, a 24-hour ECG recording on 13 freedivers and 13 sedentary controls has shown that freedivers have a 20.6% lower HR and all HRV parameters indices show higher PNS activity (Christoforidi et al. 2011).

One study involving HR and HRV studied the trigeminocardiac and the apnea induced responses and their diurnal variation in 18 young men. They performed diving tests twice three times per day (at 09:00, 13:00 and 17:00) in which in a sitting position the subjects first put their face in cold water (1.9–3.1 °C) with apnea at mid-inspiration for as long as possible. All tests showed a significant increase in HRV measures that indicate PNS activity as well as a decrease in HR. The reaction was significantly stronger in the morning and decreased in the later daily measures (Konishi et al. 2016). In warm water (27°C) the trigeminocardiac part of the diving responses did not seem to play a significant role. Head out of water immersion was a powerful stimulus on the ANS, mainly on the PNS part in warm pool conditions (Shipke et al. 2001).

Not only hyperbaric conditions, but also the oxygen partial pressure, and diving responses influence the ANS activity during diving. Ten US Navy divers who performed resting dives for 6 hours on five consecutive days showed that repeated diving caused a decrease in vagal tone and a less responsive cardiovascular system (Berry et al. 2017). A study of 10 subjects performing a challenging task in a 20-minute dive at 5 meters depth in warm water (27.5°C) showed a significant decrease in PNS activity during the dives compared to pre and post dive measurements most likely due to psychological stress (Flouris et al. 2009). A case report where an unexpected stressful situation occurred during HRV recording during diving, showed diver an increase in one in both PNS and SNS activity shortly after the incident (Zenske et al. 2020).

3 AIMS OF THE STUDY

- To describe the Finnish diving population who suffered from DCI and were treated in 1999-2018, and to analyze the types of dives they do (I)
- To investigate what factors are associated with DCI in Finland (I)
- To determine if treatment for DCI is effective in Finland (I)
- To study, if argon, used as a drysuit insulating gas, provides better thermal protection than air (II)
- To investigate how the human autonomic nervous system (ANS) reacts to diving in extreme cold conditions (III)
- To study whether HRV measures reveal possible changes that could be associated with special risk factors, such as arrhythmia, in cold water diving (III)

4 METHODS

SUBJECTS AND PATIENT POPULATION

Study I: "20 years of DCI in Finland"

For studying DCI in the Finnish diving population, we retrospectively examined all treated DCI cases over the period 1999 to 2018 in Finland in two clinics. Until 2015, 60% of these patients were treated at the Hyperbaric Medioxygen Center in Helsinki, and the remaining patients at the Turku University Hospital's Critical Care Centre. From 2016 almost all hyperbaric treatments for DCI took place at the Turku University Hospital. There have been only occasional treatments in Finnish Navy and Rescue Department Facilities during the follow-up period. These are estimated to be fewer than 5% of all treatments during the period. The subject demographics are presented the results section in Table 3.

Study II and III: "Comparison of argon and air as thermal insulating gases" and "Cold water immersion's effect on HRV"

To study the differences in thermal protection of argon and air used as drysuit insulating gases, and to investigate the effect of cold-water immersion on heart rate variability (HRV), results from Naval diving equipment development tests were retrospectively analyzed. Four physically fit male Navy divers participated in the tests, which were part of routine Naval diving activities. The subjects had a mean age of 39 years (range: 25–49), a mean height of 1.78 meters (range: 1.72–1.81), a mean weight of 83.2 kg (range: 79.2–86.8), a mean BMI of 26.4 kg/m2 (range: 25–29.2), a mean body fat mass of 11.5 kg (range: 4.9–14.5) and a mean body muscle mass of 41.2 kg (range: 37.2–43.3). Participation was voluntary and all divers gave their written consent. The divers did not get any personal benefit. The study was accepted by the Logistic Department of the Defence Command Finland, consent from the Ethical Committee of Tampere University Hospital was obtained and adhered to the Declaration of Helsinki.

DATA COLLECTION

Study I

To study DCI treatments in Finland data was collected from the medical records of the two aforementioned medical facilities. Previously, case record data collection was less systematic, with missing data, but later became more structured. The total number of retrieved DCI patient cases was 581, but 10 patients were excluded because in two cases a diagnosis of DCI could not be confirmed, in two cases too much data were missing for the analysis, and six cases were breath-holding divers who were treated for DCI-resembling symptoms. Hence, the final number of cases was 571.

Study II and III

To study the differences between argon and air as drysuit thermal insulating gases and to examine the HRV method to study ANS responses to diving in very cold water, measurements were analyzed retrospectively from data gathered during military diving equipment development testing.

DEFINING SUBGROUPS, DIVING EQUIPMENT AND OTHER VARIABLES

Study I

For analysis in the DCI-study patients were divided into technical divers (tech; n = 200) and non-technical divers (non-tech; n = 371). Technical diving was defined as using mixed breathing gases, using a closed-circuit rebreather, using air or EAN and performing planned decompression diving with decompression stops using either air, EAN or oxygen as an accelerated decompression gas. Figure 9 shows the technical and non-technical dives separately for each years of the study. Divers were divided in highly qualified and less qualified divers based on their certification level. Highly qualified divers (n = 307) had a Confédération Mondeale des Activitiés Subaquatiques (CMAS) certification level of P3 (or equivalent) or higher. A less qualified diver (n = 203) possessed a CMAS P1-2 level certification or equivalent. The certification level was not known for 61 divers. Cold-water diving was performed in areas where the water temperature was 4–10°C even in the summer at diving depths. Dives in Southern Europe, Asia or Africa were defined as warm-water diving. Open water and overhead environments (waterfilled mines or caves) were defined in cases where the information was present (n = 542).

Study II and III

The diving equipment in all dives in studies II and III was standard military diving equipment for Arctic conditions. This consisted of: a regulator mask, drysuit, diving hood, diving gloves, diving underwear, 70% merino wool socks and elbow and knee warmers and 100% merino wool polo skirt and pants. The breathing gas was air in all dives. In study II argon was used as the drysuit insulating gas on seven dives; air was used on seven dives.

PROCEDURE

Study I

Divers who developed DCI and underwent hyperbaric oxygen treatment had been diving for recreational or occupational purposes.

Study II

The comparison of argon and air was done by measuring the area-weighted skin temperature and deep-body temperature for four divers during 14 dives, 7 dives with argon and 7 dives with air. The dives were conducted in winter during a five-day period near the Arctic Circle. Each diver dived the same number of dives with argon and air, thus acting as their own reference. The dives per diver were as follows: Diver 1: two dives (start time of dives: day 3 10:15, day 5 11:20), Diver 2: four dives (start time of dives: day 3 09:30, 13:10, day 5 10:05), Diver 3: two dives (start time of dives: day 3 10:20, day 5 11:20) and Diver 4: six dives (start time of dives: day 1 12:30, 15:45, day 2 15:00, day 4 09:50, 15:20, day 5 13:20).

During the five-day testing period, the air temperature varied from -23.0°C to -3.4°C. The river in which the dives were conducted was frozen. A hole was made in the ice layer to allow the divers to enter the water. The diving equipment was put on with the help of assisting personnel in a room with a consistent temperature of 18°–19°C. Thermistors were placed at the same time on standardized locations (forehead; right scapula; left upper chest; right upper arm; left lower arm; left hand; right anterior thigh; and left calf) (ISO 15027-3:2012(E)). Excess air was vented from the drysuit prior to diving with argon by carrying out a special flushing and refilling procedure. This procedure was repeated three times to ensure that the air was replaced with argon and that the argon was distributed to all parts of the suit. The divers carried out the procedure carefully to prevent the buildup of heat before the dive and creating a bias in the data.

After all preparations, the divers walked a short distance to the diving site and commenced the dive without further delay. The subjects descended to a depth of 6 meters and remained motionless in a horizontal position at the bottom of the river for 45 minutes. Slow hand and leg movement was permitted. The water temperature was -0.5°C during all dives. A consistent water current at the diving spot increased heat loss during the dives.

Study III

To study HRV changes due to cold diving we evaluated results from tests that were performed for a three-day period in winter near the Arctic Circle. Four divers dived eleven times in total during the tests as follows: Diver 1: 2 dives (start time of dives: day 1 10:16, day 2 11:11), Diver 2: 3 dives (start time of dives: day 1 10:21, day 2 11:13, day 3 1121), Diver 3: 3 dives (start time of dives: day 1 09:31, day 2 12:30, day 3 10:06) (from one dive data of 0-10 min was included because after this physical activity was not regulated) and Diver 4: 3 dives (start time of dives: day 1 09:51, day 2 15:20, day 3 13:20) (from all 3 dives 0-10 min included because after this physical activity was not regulated). The subjects dived maximally once a day. During the test days divers had a normal sleep-awake cycle with a minimum of six hours sleep. No exercise was allowed four hours before the dives.

During the test days, the air temperature varied from -13 to -24 °C. The water temperature was measured as 0°C at the diving spot during all dives. The diving equipment and sensors were put on with the assistance of staff members in a consistent room temperature of 18–19°C. After preparation the divers walked to the river where an ice hole had been bored and performed their dive without further delay. The participants dived to a depth of 6 meters where they remained motionless in a prone position for 80–91 minutes (n = 7). Other dives (n = 4) had the same protocol at the beginning of dives (0-10min), and thus only the 10 first minutes of these dives were included in the study.

MEASUREMENTS AND STATISTICAL ANALYSIS

Study I

Statistical analyses were conducted with the IBM SPSS Statistics program (IBM Corp, Armonk (NY), USA), version 24. Continuous variables were assessed for normality using the Shapiro-Wilk test, group comparisons were done using Student's *t*-test for normally distributed variables and the Mann-Whitney U test was used to calculate non-normally distributed variables. Dichotomous variables were compared using the Chi-square test. A *P*-value of 0.05 or smaller was considered significant.

Study II

Rectal deep body temperature (T_{rect}) was measured with data storage tags (DST) using a Star-Oddi sensor. Skin temperatures were recorded with an ACR Smartreader Plus 8-system at eight standardized skin sites: the forehead; right scapula; left upper chest; right upper arm; left lower arm; left hand; right anterior thigh; and left calf (ISO 15027-3:2012(E)) every five minutes.

In addition to the objective temperature measurements, each diver reported their subjective evaluation of their operational ability every five minutes on a scale of 1 to 4, with 1: no ability at all to perform easy tasks, 2: a major drop in operational ability, 3: a minor drop in operational ability, and 4: normal performance ability.

The comparison of argon and air was made by comparing the area-weighted skin temperature (T_{skin}) of the groups. To evaluate the change in body temperature in the two groups the change in mean body temperature (MBT) was compared. The MBT was calculated with the following modification of Burton's formula, which was a combination of the skin Tskin and rectal Trect [13]:
$\Delta MBT = \Delta T_{rect} \times 0.65 + \Delta T_{skin} \times 0.35.$

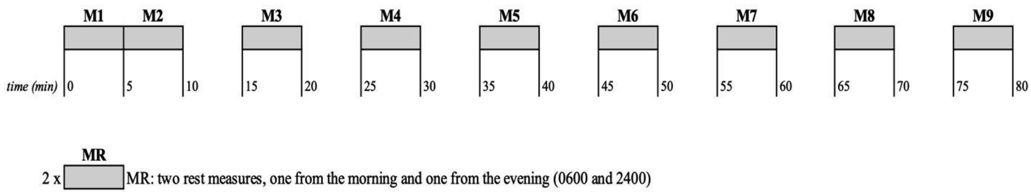
To evaluate the T_{rect}, T_{skin} and MBT changes a linear mixed-effects model was used with main effects and the interaction between group and time. Both the varying slope and varying intercept were fitted for ID. The analyses were made using the R program (R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria).

The difference in operational performance was compared using a Mann-Whitney U test.

Study III

We recorded short-term (five minutes) heart RR intervals at a 1000 Hz sampling frequency using the HRV Bodyguard device (Firstbeat Technologies Ltd., Jyväskylä, Finland). From these recordings the heart rate variability (HRV) was analyzed with the Kubios HRV Standard (Ver. 3.1) program (Kubios Ltd., Kuopio, Finland), from the recordings from diving subjects for 11 short-term measures (M1-M9 and MR) (Figure 9). We used the program's automatic artefact correction feature to correct corruption in data, and we utilized the program's time series trend removal tool for each subject before analysis (Lipponen et al. 2017). Point 0 min is the start of the dive.

Figure 9: Times of the short-term HRV measures used in the study: M1 (0-5min), M2 (5-10min), M3 (15-20min), M4 (25-30min), M5 (35-40min), M6 (45-50min), M7 (55-60min), M8 (65-70min) and M9 (75-80min). 0 min equals the beginning of the dive. Additional resting values (MR) were measured at 06:00 and 24:00.



We used three time-domain measures and five frequency-domain measures:

Time-domain measures: the mean heart rate (HR_{mean}) in bpm, the standard deviation of NN intervals (SDNN) in ms, and root mean square of successive RR interval differences (RMSSD) in ms.

Frequency-domain measures: absolute total power (TP) in ms^2, absolute power of the very low frequency band (VLF) in ms^2, absolute power of the low frequency band (LF) in ms^2, absolute power of the high frequency band (HF) in ms^2, and ratio of LF to HF power (LF/HF).

Temperature measures (Trect and Tskin) were recorded in the same way as in Studies I and II, and the MBT was calculated using Burton's formula with a 5 min interval throughout the dives.

A linear mixed-effects model was run with the main effects and interaction between the group and time. Both a varying slope and varying intercept were fitted for ID. The analyses were conducted with the R program (R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria).

HRV analyses were performed for MR–M1 and M1–M2. For the longer dives with no physical activity ($n = 7$) analyses were carried out for M2–M9. Temperature analyses ($n = 7$) were made for M1–M9 except for T_{rect} that seemed to show an increase from M1–M3 (M1–M3 and M3–M9 were analyzed separately).

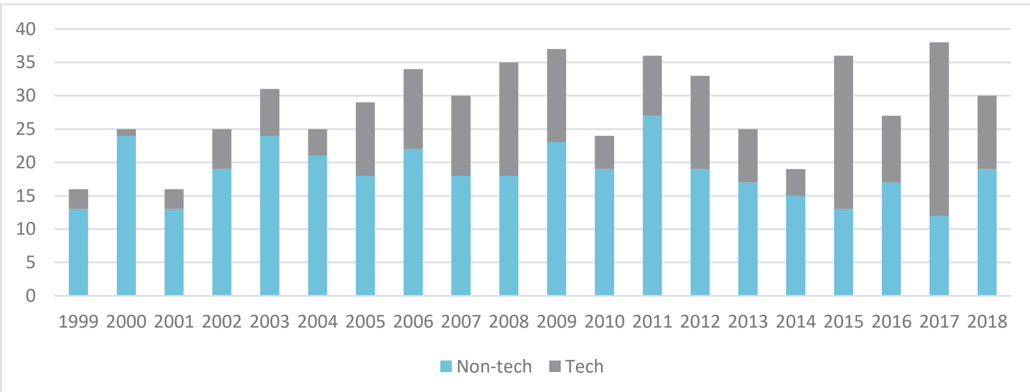
5 RESULTS

Study I

EPIDEMIOLOGY

From 1999 to 2018 the number of treated DCI cases in Finland varied from 16 to 38 cases per year, with an average of 29 cases. There seemed to be a shift towards technical diving, since the number of cases of technical divers treated for DCI seemed to increase as shown in Figure 10. This most likely shows an increase in the popularity of technical diving among Finnish divers.

Figure 10: The number of divers treated for DCI per year. Divers were divided into technical and non-technical divers based on the gas and the dive technique they had used during the incident dive. Complete data was available from all divers in the study: n = 571.



DIVERS

A comparison of non-technical and technical divers showed that technical divers were more likely to be male (87% vs. 73%, $P < 0.001$), older (mean (SD): 38 (8) years vs. 35 (8) years, $P < 0.001$) and more highly qualified (93% vs. 41%, $P < 0.001$). No difference was seen between the groups in medical conditions or in the use of medication. No difference was seen in the prevalence of smoking, and its prevalence was similar to the general population (Finnish Institute for Health and Welfare, 2018). The occurrence of previous DCI was similar in both groups, but surprisingly high (43% vs. 34%, $P = 0.081$), suggesting that most divers continued diving after successfully treated DCI.

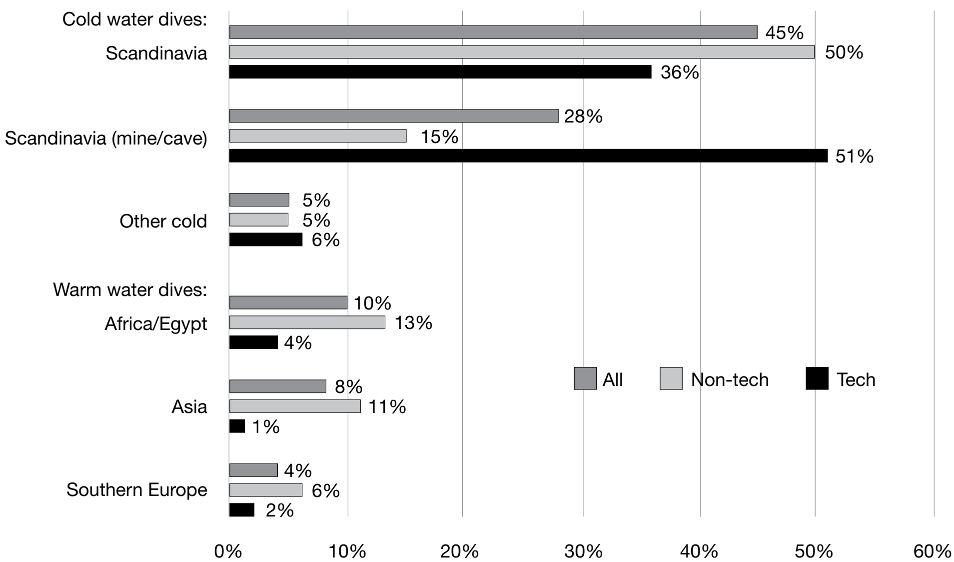
Table 3: Baseline characteristics for divers treated for DCI in Finland 1999-2018. The data is shown in numbers (%). Information on previous DCI was available for technical: n=135 and non-technical divers: n=194 and on the qualification level ≥ P3 for technical: n=175 and non-technical divers: n=132. The percentages are based on the available data.

	Males	Age mean (range)	Qualification ≥P3	Underlying disease	Medical treatment	Smoking	Previous DCI
Non-technical	272 (73)	35 (18-62)	132 (41)	56 (15)	40 (11)	32 (9)	65 (34)
Technical	174 (87)	38 (18-62)	175 (93)	26 (13)	25 (13)	19 (10)	58 (43)
All	446 (78)	36 (18-62)	307 (60)	82 (14)	65 (11)	51 (9)	123 (37)

INCIDENT DIVE

In 35% of the cases the incident dive was defined as a technical dive. In the technical group trimix (36%) or CCR (20%) was used in 56% of these cases. Detailed information on the location of the incident dive (technical dives and non-technical dives separately) is presented in Figure 11.

Figure 11: The diving location of the incident dive, for all, technical and non-technical divers separately. Cold water dives and warm water dives are shown under their own headings. "Scandinavia" does not include mine/cave dives in Scandinavia, these are presented as a separate group. "Other cold" includes cold dives in other locations, e.g., deep-sea dives and dives in northern countries outside Scandinavia. Information was available for technical: n=193 and non-technical: n=349 dives. The percentages are based on the available data. From DHM Journal, Vol 49(4). Reproduced with permission.



There were many differences between technical and non-technical dives. In the technical group the dives were mainly done in a cold-water environment (93% vs 70% in non-technical dives, $P < 0.001$). In the technical group the median maximum depth of the dive was 45 msw/ mfw (range: 11–209) vs. 25 msw/mfw (range 4–56) for non-technical dives ($P < 0.001$), and the median duration of the dives for technical dives was 65.5 minutes (range: 17–420) vs. 35 minutes (range: 4–238) for non-technical dives ($P < 0.001$). A large proportion of the dives resulting in DCI were performed in an overhead environment, for example old, flooded mines, caves, or quarries. These locations have good visibility compared to lakes and seaside locations, but nonetheless the conditions are demanding, with water temperatures in the locations being 4°C all the year round. Moreover, the overhead environment causes an additional risk factor for diving, for example rapid surfacing is not possible and the risk of disorientation in caves is present. In the technical divers' group over half (51%) of the incident dives were performed in these overhead locations.

CONTRIBUTING FACTORS

When available possible contributing factors were assessed. Possible contributing factors were elucidated in 76% of all cases. These are presented in Figure 12. Such factors included: consecutive diving days (technical: 52% vs. non- technical: 54%, P = NS); multiple dives per day (technical: 21% vs. non-technical: 47%, $P < 0.001$) and flying after diving (technical: 14% vs. non-technical: 38%, $P < 0.001$). These are all associated with diving vacations and safaris in warm water environments.

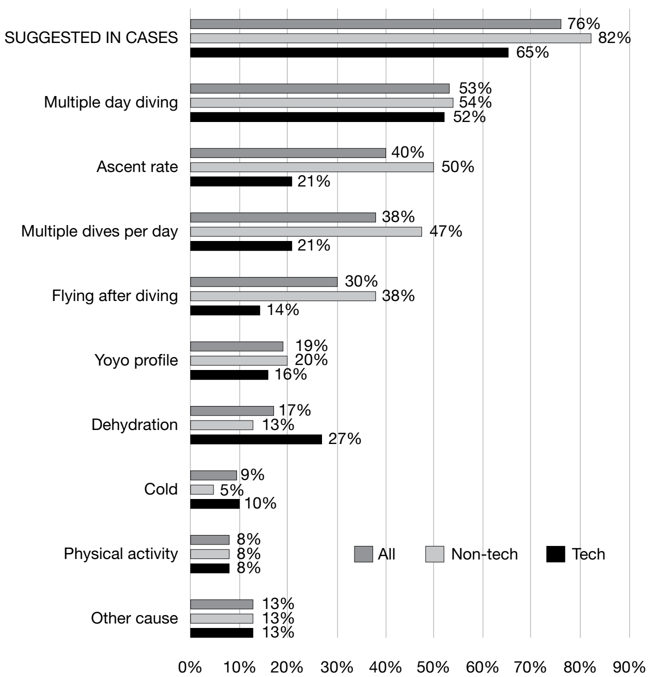


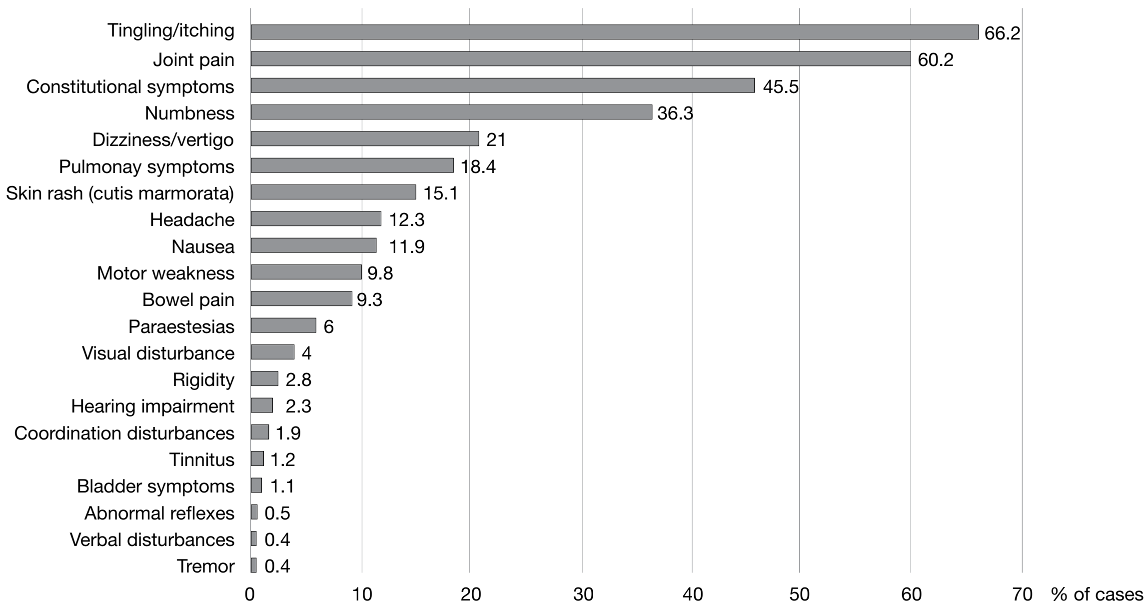
Figure 12: Suggested contributing factors for DCI for all, technical and non-technical divers separately. Other causes include traveling by road over high mountains (as is done by many Finnish divers on diving trips to Norway), technical problems, problems with breathing gas and acute medical condition. Data was available for all divers (n = 571). From DHM Journal, Vol 49(4). Reproduced with permission.

An overly fast ascent rate was reported in 50% of cases in the non-technical group (vs. technical: 21 %, $P < 0.001$). For technical dives, deeper and longer dives *per se* may have increased the risk and incidence of DCI. Additional reported factors for the technical dives were: consecutive days diving (52%); dehydration (technical: 27% vs. non-technical: 13 %, $P = 0.001$) caused by these long dives; and cold water (technical: 10% vs. non-technical 5%, P = NS) that reduces peripheral tissue perfusion and elimination of inert gas.

SYMPTOMS OF DCI

Symptoms of DCI are presented in Figure 13. The most common symptom was tingling/itching (66.2% of all cases) followed by musculoskeletal pain (60.2%), constitutional symptoms (tiredness, light-headedness, excessive fatigue and malaise, 45.5%), numbness (36.3%) and dizziness/vertigo (21%). More serious DCI manifestations included pulmonary symptoms (18.4%) and neurological symptoms (17.7%). Neurological symptoms included: motor weakness (9.8%), visual disturbances (4%), coordination disturbances (1.9%), bladder symptoms (1.1%), abnormal reflexes (0.5%) and verbal disturbances (0.4%).

Figure 13: Percentages of cases experiencing particular symptoms prior to the first recompression treatment. Constitutional symptoms include tiredness, light-headedness, inappropriate fatigue, and malaise. Information was available for all divers (n = 571). From DHM Journal, Vol 49(4). Reproduced with permission.



We made a comparison between the symptoms in the technical and non-technical diver groups for the last three years of the data, when the data was more comprehensive (during years 2016 to 2018 all were treated in Turku University Hospital). There were significant differences in the prevalence of tingling/itching (technical: 49% vs. non-technical: 69%, $P = 0.05$); skin rashes or cutis marmorata (technical: 40% vs. non-technical: 19%, $P < 0.05$), and headaches (technical: 4% vs. non-technical: 17%, $P < 0.05$).

TREATMENT OF DCI

First aid oxygen (FAO_2) was given on site to 31% of all patients. However, the use of FAO_2 was more common in the technical divers' group compared to non-technical divers (52% vs. 19%, $P < 0.001$). This was most likely due to the higher qualification and training levels in the technical divers' group and due to the availability of oxygen on-site. The median delay to recompression was also clearly shorter in the technical divers' group compared to the non-technical divers: 24 h (range: 1–510) vs. 48 h (range: 1–1008) ($P < 0.001$).

USN TT6 or an extended version of it was the most common primary treatment protocol (used in 79% of cases). In 55% of the cases the divers received at least one additional hyperbaric treatment. No difference was seen between the technical and non-technical diver groups in this respect. The mean number of retreatments was 1.36 (range: 0–15). Recompressions had very different protocols over the years. The most commonly used protocol was 90–104 minutes at 243–253 kPa in the earlier years of the study. In the later years USN TT6 was the most commonly used protocol. USN TT5 was only used when patients had mild residual symptoms after the first treatment.

The results of the treatment were good in most cases. 82% of patients in both groups were completely asymptomatic after hyperbaric oxygen treatment. 14% of cases showed mild residual symptoms. Only 4% were unfit-to-dive after treatment. The unfit-to-dive included patients with both clinical reasons, such as permanent hearing impairments or vestibular residua and patients that had decided themselves not to return to diving, for example because of psychological reasons.

Study II

None of the divers experienced any complications during the tests. The physiological critical temperature levels (Lotens 1988, ISO 9886 2004) were not recorded during the dives (Figures 14 and 15). The mean T_{rect} and mean T_{skin} of the argon and the air group separately are shown in figures 14 and 15. The change in MBT for both groups over time is presented in Figure 16.

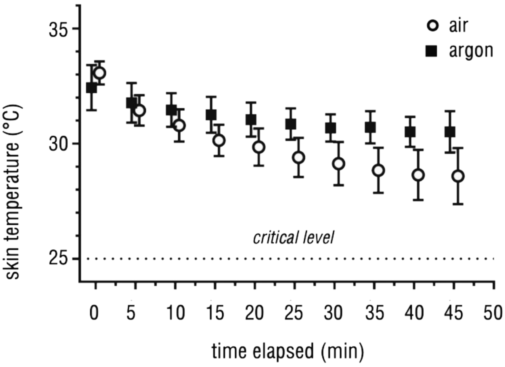


Figure 14

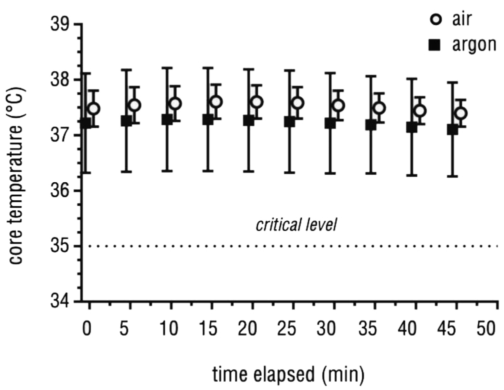


Figure 15

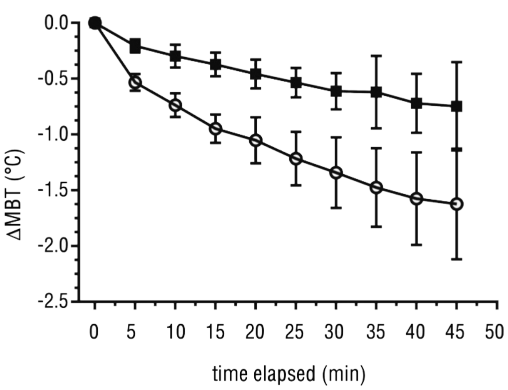


Figure 16

Figure 14: Area weighted skin temperature for argon (n = 7) and air (n = 7) dives in near freezing water; means and standard errors shown. Critical level for skin temperature are marked with a separate line (Lotens 1988, ISO 9886 2004)

Figure 15: Rectally measured deep body temperature for argon (n = 7= and air (n = 7) dives in near freezing water; means and standard errors shown. Critical level for core temperature marked with a separate line (Lotens 1988, ISO 9886 2004).

Figure 16: The change in calculated mean body temperature ΔMBT for argon (n = 7= and air (n = 7) dives in near freezing water; means and standard errors shown.

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For the Trect measurements the analyses did not show any significant change in temperature, nor was there any difference between the two groups.

The Tskin measurements showed a significant decrease over time on the air dives (ΔT_{skin} = -4.16°C, SE = 0.445, $P < 0.001$), and a significantly smaller reduction on the argon dives compared to the air dives (difference between groups = 2.26°C, SE = 0.358, $P < 0.001$).

The ΔMBT measurements showed a significant reduction in temperature over time on the air dives (ΔMBT = - 1.53°C, standard error (SE) = 0.153, $P < 0.001$), and a significantly smaller reduction on the argon dives compared to the air dives (difference between groups = 0.77°C, SE = 0.117, $P < 0.001$).

There was no significant difference in the subjective evaluation of operational ability. One diver (diver 4) reported a subjective reduction in his operational ability on a scale (1-2-3-4) from 4 to 3 during two dives (at 25 minutes and at 35 minutes)—both dives in were the air group.

Study III

Results from HRV analyses are shown in Figures 17 a–h.

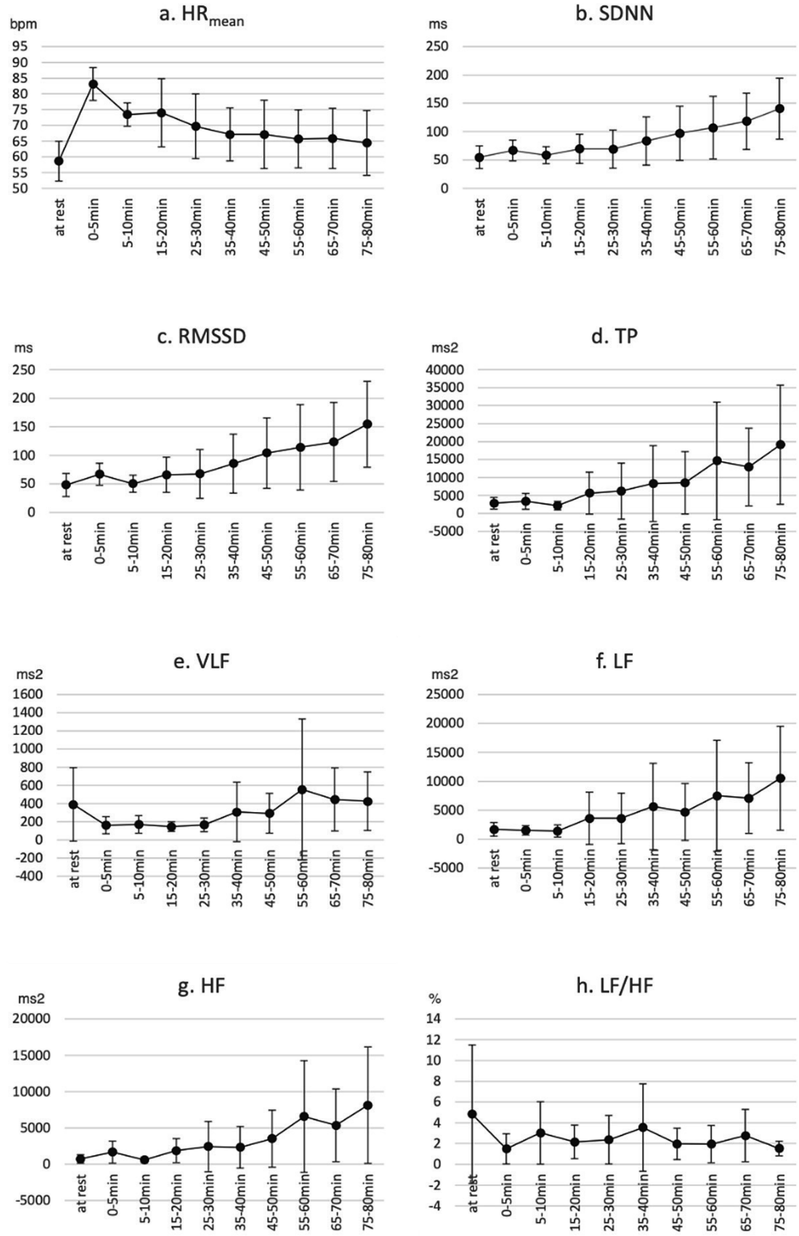

Figure 17 a. – h.

Three time-domain measures:

(a) Mean heart rate (HRmean)
(b) Standard deviation of NN intervals (SDNN) and
(c) Root mean square of successive RR interval differences (RMSSD)

Five frequency-domain measures:

(d) Absolute power of the very low frequency band (VLF)
(e) Absolute power of the low frequency band (LF)
(f) Absolute power of the high frequency band (HF)
(g) Absolute power of the high frequency band (HF)
(h) ratio of LF to HF power (LF/HF)

Measures are presented:

MR: at rest (n=22),
M1: 0-5min (n=11),
M2: 5-10min (n=11),
M3: 5-20min (n=7),
M4: 25-30min (n=7),
M5: 35-40min (n=7),
M6: 45-50min (n=7),
M7: 55-60min (n=7),
M8: 65-70min (n=7),
M9: 75-80min (n=7).

Means and standard errors shown.

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a. HR_{mean}: From MR–M1 the heart rate increased significantly by 25 bpm (Standard error (SE) = 1.86, $p < 0.001$). From M1–M2 the heart rate decreased significantly by 9.08 bpm (SE = 1.86, $p < 0.001$). From M2–M9 (n = 7) the heart rate decreased significantly by 9.66 bpm (SE = 0.36, $p < 0.001$).

b. SDNN: From MR–M1 there was a significant increase of 12.22 ms (SE = 5.79, p = 0.04). From M1–M2 there was a non-significant decrease of 6.99 ms (SE = 5.79, p = 0.23). From M2–M9 (n = 7) there was a significant increase of 78.61 ms (SE = 1.87, $p < 0.001$).

c. RMSSD: From MR–M1 there was a significant increase of 14.67 ms (SE = 6.09, p = 0.02). From M1–M2 there was a significant decrease of 12.92 ms (SE = 6.09, p = 0.04). From M2–M9 (n = 7) there was a significant increase of 97.86 ms (SE = 2.28, $p < 0.001$).

d. TP: From MR-M1 and M1–M2 there was no significant change. From M2–M9 (n = 7) there was a significant increase of 15044.61 ms^2 (SE = 441.67, $p < 0.001$).

e. VLF: From MR–M1 there was a significant decrease of 172.90 ms^2 (SE = 60.98, p = 0.008). From M1–M2 there was no significant change (increase 6.27 ms^2, SE = 60.98, p = 0.91). From M2–M9 there was no significant linear change.

f. LF: From MR-M1 and M1–M2 there was no significant change. From M2–M9 (n = 7) there was a significant increase of 7675.92 ms^2 (SE = 273.75, $p < 0.001$).

g. HF: From MR–M1 there was a near-significant increase of 678.63 ms^2 (SE = 344.48, p = 0.059). From M1–M2 there was a significant decrease of 835.73 ms^2 (SE = 344.48, p = 0.022). From M2–M9 there was a significant increase of 6983.41 ms^2 (SE = 208.23, $p < 0.001$).

h. LF/HF: From MR–M1 there was a near-significant decrease of 2.46% (SE = 1.45, p = 0.10). From M1–M2 there was a significant increase of 3.05% (SE = 1.45, p = 0.045). From M2–M9 (n = 7) there was no significant linear change.

The T_{skin} measurements showed a significant decrease of 3.92 °C (SE = 0.05, $p < 0.001$) over time. T_{rect} first had a non-significant increase of 0.051 °C (SE = 0.068, p = 0.46) (0 – 15 min). From 15–75 min there was a significant decrease of 0.66 °C (SE = 0.009, $p < 0.001$). MBT showed a significant decrease of 1.84 °C (SE = 0.02, $p < 0.001$) over time.

6 DISCUSSION

Study I

To my knowledge, our study is the first to describe DCI in the Finnish diving population. Through this study we also obtained an overview of where Finnish divers dive and what kind of diving is popular in Finland. The majority of dives are performed in a very cold diving environment, which adds challenges and risks to the divers. Our study suggests an increase in technical diving, where mixed breathing gases and closed-circuit rebreathers are used, since the number of technical divers treated for DCI seemed to increase in the later years in the follow up time. However, annual numbers of DCI cases treated with HBOT remained at a constant level during the 20-years period. Technical diving means often more demanding, longer, and deeper dives, hence this special type of diving per se means an elevated risk of DCI even for the well-educated divers that do technical diving.

When compared to a large study on DCI from Denmark (Svendsen et al. 2016), our study shows a higher number of cases treated for DCI per year (mean: 29 in Finland vs. 14 in Denmark (Svendsen et al. 2016)), even though the population is similar in both countries. On the other hand, there are no official statistics on diving activity in Finland or in Denmark, and without any accurate denominator it is very difficult to draw conclusions on the differences between the incidence of DCI in these countries. It must also be noted that many Finns receive their diving training abroad in diving holiday locations, and they are not therefore recorded in the statistics on Finnish diving certifications.

In our study the diver demographics resembled the previous studies from Denmark (Svendsen et al. 2016) and the other large study from New Zealand (Haas et al. 2014). The majority of treated DCI patients were males, with 78% vs. 79% (Svendsen et al. 2016) vs. 81% (Haas et al. 2014) and mean age was 36 years vs. 35.5years (Svendsen et al. 2016) vs. 33.6years (Haas et al. 2014). An interesting finding in this study was that a significant number of treated DCI patients were technical divers. In the study from New Zealand, in only 3.4 % of the incident dives had mixed breathing gases been used. In that study a closed-circuit rebreather had been used in only 1% of dives. In our Finnish data the latter percentage was 6.8%.

The mean diving depth was similar in the Finnish non-technical group (25 msw/mfw) compared to that of the incident dives in New Zealand (25.8 msw/mfw), whereas the technical divers went deeper in the Finnish cohort. When adding to that the effects of cold, one can conclude that the Finnish divers who developed DCI, seemed to perform very demanding dives which may provide an explanation as to why has not been a decrease in the number of annually DCI cases as has been seen in New Zealand or Denmark. The Danish study did not provide details on the incident dives nor of used breathing gases. A noteworthy finding in our study is the great number of patients with previously treated DCI (37%). This could indicate that Finnish divers are strongly committed to diving or show a tendency to do risky and demanding diving.

Tingling/itching, musculoskeletal pain, constitutional symptoms, numbness, and dizziness/vertigo were the most common symptoms in the Finnish study. These were similar in other published DCI studies, although the prevalence of the symptoms varies (Vann et al. 2011, Svendsen et al. 2016, Haas et al. 2014). A comparison of the subgroups' technical and non-technical dives for the last three years of the study showed a surprisingly similar pattern in both groups. Only for tingling/itching, skin rash/cutis marmorata and headaches was there a significantly different prevalence between the groups. The similarity in the symptom profile in the subgroups is an unexpected finding, because one could have anticipated that the long and deep dives in the technical divers' group would have caused the slow tissues to absorb more inert gas and when ascending due to the cold Arctic conditions, there would have been vasoconstriction in the peripheral tissues causing exaggerated bubble formation in supersaturated tissues.

The use of FAO_2 was still relatively uncommon, although oxygen provider courses have been available for many years and some training organizations require certification from these courses when progressing through training. In our study only 31% of the divers received FAO_2 on site. Technical divers used FAO_2 twice as often compared to the non-technical group, which is most likely due to the good availability of breathing oxygen on the dive site. It is also likely that many mild DCI cases never encounter medical facilities as they treat symptoms with in-water recompression using normobaric oxygen. The use of FAO_2 resembled that in previous studies. These earlier studies show that 23– 47% of divers were provided with FAO_2. The USN TT6 with or its modifications were the most commonly used treatment protocols in all three studies (79% vs. 69% (Svendsen et al. 2016) vs. 65% (R. M. Haas et al. 2014). The number of additional recompressions was also similar in all three studies (1.36 vs. 1.27 (Haas et al. 2014)).

HBOT was effective in our study. 82% of cases became completely asymptomatic after treatment, and 96% reached near complete recovery. This is different compared to the two earlier studies, that showed residual symptoms in in 22– 55% of patients at hospital discharge (Svendsen et al. 2016, Kot et al. 2008, Gempp et al. 2010, Blatteau et al. 2011, Aharon-Peretz et al. 1993). An explanation for this large difference could be the difference in the re-treatment protocols. Additionally, when hospital discharge occurs within 12 hours after hyperbaric treatment, as was often the case in the Finnish study, mild re-occurring symptoms might still be absent at this point. Symptoms might re-occur 12–24 hours after treatment for some patients (Tempel et al. 2006), which might not be observed in this study. The majority of cases in the Finnish study were asymptomatic after one or two treatments. If required, patients could be treated up to 15 times until they were asymptomatic or a plateau in improvement of symptoms had been reached. For repetitive hyperbaric treatments there is no gold standard protocol, although HBOT *per se* is recommended (Vann et al. 2011).

Noteworthy in this study was the high number of previously treated DCI in cases in both the technical and non-technical diver groups. One explanation for this could be the good treatment outcomes. If divers recover completely from DCI, they are more likely to continue diving, in contrast to divers with residual symptoms after treatment. It is also possible that among the Finnish divers there are a large proportion of highly motivated and focused divers that dive a lot and do demanding diving, which per se increases the likelihood of getting DCI. These divers also tend to continue to dive after an adverse event. The high number of technical divers in this study lends credibility to this hypothesis.

During the 20-year period in this study the hyperbaric retreatment protocols have varied. The majority of the cases received a shorter secondary treatment of 90 minutes at 243 kPa, which was similar in the other two studies (Haas et al. 2014, Bennett et al. 2012). In the later years of the study, the most frequent retreatment protocol was USN TT6, with or without an extension, or USN TT5. Observations have shown that longer HBOT leads to better clinical outcomes than shorter protocols irrespective of the severity of the symptoms. However, this observation was from primary treatment and not retreatment (Hadanny et al. 2015). The evidence in this study is also weak. Another study where USN TT6 and USN TT5 were compared as primary treatment showed better outcomes with the longer tables (Sayer et al. 2009), but as mentioned, this was a comparison of primary treatments and definitive conclusions cannot be made on secondary treatments. Moreover, when considering retreatments, a cumulative and toxic effect of oxygen on lungs and CNS must be taken into account (Thorsen et al. 1998, Donald et al. 1947).

Study II

This is the first study that shows the beneficial properties of argon used as a drysuit insulating gas on divers. In our conditions and for our subjects, argon showed better insulating properties compared to air. Because the groups were small and not well balanced one should be careful not to draw conclusions on its benefit in all conditions.

The divers' subjective reports showed a drop in operational ability in two dives in the air group. These subjective reports support the objective results, although these were not statistically significant and can therefore not be seen as evidence of the superiority of argon, but these are in line with the objective measurements.

When using only core temperature as the only objective measurement, as was done in an earlier study to compare argon and air used as inflation gas (Vrijdag et al. 2013) no significant difference was seen between the groups. The skin temperature readings give a more precise picture of the properties of the insulating layer. Moreover, the combination of both skin and deep body temperature provides a better view of the change in total body temperature. MBT has been shown to be an accurate method for combining these temperature measures in the form of a two-compartment model (Lenhardt et al. 2006). The problem with these measurements is that for evaluating heat loss, the method does not take into account that the temperatures measured are influenced by both heat loss, heat production, and heat distribution. In a cold environment, the body's thermoregulatory mechanisms normally cause a slight increase in the core temperature, wherefore using only the core temperature to compare the two gases would not be optimal. This could explain why there was not a difference between groups in the study by Vrijdag et al. (2013). Additionally, in their study the water temperature was not very cold (13°C) which lessens the significance of additional thermal insulation for a near thermoneutral diver.

Another earlier study from Norway measured both deep body and skin temperatures in divers at water temperatures of -1°C to + 4°C (Risberg et al. 2001). This study did not show a significant difference between the argon and the air group. As the authors discuss in their article, the divers were in a horizontal position during the dives, which allowed the suit to squeeze against the lower parts of the body, and thus causing the insulating gas layer around the downward facing parts to decline. This meant that over large areas the insulating layer between the diver and the cold surrounding water was rather thin (Risberg et al. 2001). This can partly explain why there was not a significantly difference in the results between the groups in the study.

In our study the divers were in a similar horizontal position as the divers in the previously mentioned Norwegian study. The difference to that study was that they had thicker layers of clothing under the outer suit layer, especially on the parts facing downwards. This ensured that at all times there remained a distance between the diver's skin and the outer layer of the drysuit, thus a gas layer was also present at all times. Divers also used additional knee and elbow warmers to ensure the same thing around their moving joints. Moreover, the divers used porous, gas binding merino wool layers as undergarments to hold the gases as well as possible. The drysuits were also large enough to fit all the clothes, and to enable a sufficient amount of gas to prevent the suit squeezing against the body.

There are not many disadvantages to using argon as a drysuit inflation gas. As the most prevalent noble gas in our atmosphere, extracting it is not too costly. If used in greater proportions however, economical, and logistical factors must be noted. The theoretical possibility of confusing an argon gas cylinder with another breathing gas containing cylinder could have fatal consequences to the diver through hypoxia. However, in a well-functioning diving community with good routines the risk is not highly relevant. A very uncommon but described risk of argon is urticaria and vestibular dysfunction (Lambertsen et al. 1975), but in practice it is hardly never seen.

To benefit from the thermal properties of argon, it is important to avoid the drysuit squeezing against the body. If this is not attained the role of the insulating gas loses its benefit. The easiest way to keep the outer layer of the suit at a good distance from the diver’s body is to use a sufficiently thick layer of clothing under the suit, especially for the parts facing downwards. Moreover, it is important to carry out a thorough suit flushing procedure to ensure that normal air is effectively replaced by argon. Since an overly large amount of clothing under the drysuit may restrict the diver’s mobility and buoyancy control, the focus should be more on the material structure and material thickness used, rather than on adding too many clothing layers. The amount of clothing in study II was relatively standard for diving in very cold conditions.

A significantly lower decrease in T_{skin} and ΔMBT in the argon group compared to the air group seen in our study supports the hypothesis that divers who dive in Arctic conditions could benefit from using argon as a drysuit insulating gas. The risks caused by the cold conditions (Davis et al. 1975, Bridgman 1990, Gerth 2015, Pendergast et al. 2015) outweigh the theoretical risks of using argon (Lambertsen et al. 1975). Even a small improvement in thermal insulation can be relevant in these very extreme conditions. For example, in most DCS cases from cold water diving, cold is as least a contributing factor in developing symptoms (Pendergast et al. 2015). The divers in our study were in the water for only 45 minutes. In Finland technical divers perform much longer, deeper, and more demanding dives in similar temperatures, often in an overhead environment. Long dives mean also long decompression times, which comprise a greater risk in a cold environment. When adding to this that technical divers often use helium mixtures as breathing gases, the risk of temperature loss additionally increases because of the poor thermal coefficient of helium. In these dives the use of argon may be even more beneficial, as the heat conduction of helium is higher than that of air.

Study III

A remarkable new finding in our study is that in these very cold conditions, after the first rather quick and strong parasympathetic activation in the first five minutes of the dive, the PNS activity actually decreases (from measure M1/0-5 min to measure M2/5-10 min). The first PNS increase (measure 0-5 min) can be explained by diving reflex-induced physiological changes (Vega 2017, Konishi et al. 2016, Schaller et al. 2017, Schlader et al. 2018, McCulloch et al. 2018). The following decrease in PNS activity suggests that the diving reflex-induced PNS response actually decreases in cold water shortly after the first response. This decrease has not earlier been described in the scientific literature. Our hypothesis is that the first strong PNS activation is caused by the trigeminocardiac reflex, activated by the sensation of wet and cold on the face, and this reflex quickly loses its relevance. As seen in the results section, however, later measures (measure M2/5-10 min to measure M9/75-80 min) show a successive increase after this decrease. Our interpretation is that this is caused by baroreceptor activity and thermoregulation mechanisms due to decreasing body temperature.

To our knowledge no short term HRV studies have been done on divers to study different aspects of the diving responses, hence this afore described decrease in PNS activity shortly after the beginning of the dive has not been noticed. Other ANS responses such as the concurrent increase in SNS activity caused when entering cold water may have covered up this decrease when studying the diving responses with HR as the only measure. As also seen in our study the HRmean does not reveal the decrease. Otherwise, our measures correlate well with other earlier HRV studies from diving (Schipke et al. 2001, Lund et al. 2000, Kurita et al. 2002, Flouris et al. 2009, Chouchou et al. 2009, Noh et al. 2018).

The secondary increase in PNS activity (from measure M2/5-10 min to measure M9/75-80 min) is likely to be caused by baroreceptor activation due to centralization of blood volume caused by hydrostatic pressure and cold induced vasoconstriction. The results in this study show a non-significant increase in the body core temperature (0-15 min measures) suggesting a centralization of the blood volume. This finding lends weight to this hypothesis. MBT combines both central and peripheral temperature measures, and thus it takes into account changes in blood redistribution. A 0.5°C decrease in deep body temperature has been shown to promote PNS activity (Hodges et al. 2019), which would support the idea that cold plays an important role in increasing PNS activity during the whole dive.

Since the ambient pressure was constant during the dives (6 meters at all time) one could assume that the cold was a more substantial promoter of PNS activity than pressure. Earlier studies suggest that pressure induced changes in ANS activity would be more pressure dependent than time dependent (Barbosa et al. 2010), but knowledge on this topic is still limited. On the other hand, there was a strong increase in the power of the LF-band throughout the dives, that would lend weight to the theory of ongoing baroreceptor activity. This in turn would suggest that the PNS increase was due to pressure. Most likely both mechanisms influence PNS changes at some amount. Our study does not determine how long the PNS activity would increase for in similar conditions, since the activity increased until the last measures. Theoretically strong PNS activation could have negative health effects, that could influence diving safety, for example leading to arrhythmia, atrioventricular blocks, or even sudden death (Aste et al. 2017, Vaseghi et al. 2017, Japundzic-Zigon et al. 2018, Benito-Gomez et al. 2019).

The SNS activity was estimated from the LF-band and the LF/HF ratio, and there were no significant changes at the beginning of the dives, which is in line with earlier findings for experienced divers (Schipke et al. 2001). Although, a comparison to the resting measure MR should not be seen as too reliable since the resting measures are not recorded in similar conditions as the other measures during the dives. Additionally, the LF band reflects much more than simply SNS activity. An increase in the HRmean (MR - M1/0-5min) at the beginning of the dives suggests that there would be at least some SNS activation—most likely mostly due to the uncomfortable cold sensation the diver experiences when entering the water. This implies a concurrent PNS and SNS activation, which in turn would resemble most earlier observations (Buchholz et al. 2017, Boussuges et al. 2007). These earlier observations indicate that both the diving reflex and sensation of cold also cause activation of the SNS.

After the first SNS responses to immersion the change in LF/LH ratio and HRmean indicated a decrease in SNS activity for the rest of the dive. This would indicate that cold is not a physiological nor a psychological stressor for experienced divers.

Cold water diving activates the SNS at the beginning of the dive, as described above. The diving responses also increase PNS activity as described above. If the dive also requires physical work, which activates the SNS, this will lead to a quick concurrent increase in both PNS and SNS activity which is a known risk factor for arrhythmia and sudden death (Buchholz et al. 2017, Kane et al. 2018). To reduce the risk, especially if heavy physical activity is required, we would recommend a short adaptation phase at the beginning of dives in cold water. Additionally, to reduce risks we would recommend that special emphasis would be taken on evaluating incipient signs of heart disease and recommend strict cardiovascular criteria for professional divers that operate in Arctic conditions.

LIMITATIONS

Study I

This retrospective study has some limitations, for example the long observation period meant that there were changes in data collection and treatment protocols, especially concerning retreatments. In the earlier years of the study, the collection of data was more unstructured, which means that from these years some data is missing. Moreover, there was no systematic long-term follow-up for patients treated for DCI, which means that some divers might have gotten mild reoccurring symptoms which were not recorded in this study. Additionally, in contrast some divers might have recovered totally from residual symptoms.

Study II

Our study has some limitations that have to noted. This was not a blinded study, which means that subjective reports on operational ability can only be seen as supportive data, not as evidence. The study was conducted as a field study and not in controlled conditions. On the other hand, conditions, for example, the water temperature, currents etc. were stable and the same for all dives, so this should not have influenced the results. The divers' physical characteristics (age, body fat mass, muscle mass etc.) varied a lot, but this was taken into account by every diver diving the same number of dives on both the argon and the air group. Additionally, the number of dives was small, and the groups were not well balanced. The fact that one diver contributed to a great part of the data means that conclusions cannot automatically be drawn to all possible argon divers.

Adaptation to cold is possible (Lambertsen et al. 1975). This might have occurred during the test week but was not taken into account in these tests. On the other hand, adaptation should logically have lessened the differences between the groups. An interesting thing to note are the wide confidence intervals in the T_{rect} values for the argon group. One explanation for this phenomenon could be that before the argon dives, the divers did a thorough suit flushing and squeezing procedure. Muscle work, even if it was for a short time, could have caused a redistribution of blood volume in the body. This could have had an influence on results, but this should have led to a greater ΔMBT for the argon dives because muscle work causes an increase in the peripheral blood circulation and therefore greater heat loss.

Study III

In study III the data was gathered during a field study, as in study II, and not in controlled laboratory like conditions. However, since all of the dives took place on the same spot 6 meters under surface ice, the weather did not influence the diving conditions. Even in this study the number of subjects was small, as is usual in field studies in extreme weather conditions. However, the results from this small group were significant. In future studies it would be valuable to make a controlled resting measure to define an HRV baseline while breathing the same gas as used during the dive from a regulator. In this study the resting values were taken from times the divers were in bed in the morning and in the evening, which are not necessarily the most accurate times for measuring since sleep influences possibly HRV (Penzel t al. 2016, Balasubramanian et al. 2017).

The results from our limited number of dives at a shallow depth cannot automatically be transmitted to all types of SCUBA diving. In different types of diving many other things influence HRV, for example, the heart lung interaction, physical and psychological stress, oxygen partial pressure, ambient pressure and many other factors have shown to influence the ANS.

7 CONCLUSIONS

Finnish divers dive all year round, and mostly in very challenging Arctic conditions. In our study on DCI we recognized a shift towards technical diving, although the DCI cases per year have remained constant. Highly qualified divers that dived challenging dives got DCI and this was often on dives with an overhead environment. Divers who got treated recovered well and most returned to diving. There is still room for improvement in the use of FAO_2 as only 31% received it on site.

To improve the thermal insulation in very cold Finnish diving conditions argon is a useful method. Our study showed that Tskin and MBT values fell significantly less in the argon group in the very cold conditions described in our study. This is a new finding, and it contradicts earlier studies. Finnish cold conditions cause temperature induced risks that are much higher than the theoretical risks of argon. Cold is a risk for hypothermia and decompression sickness and causes a reduction in both physiological and cognitive skills. If heat loss can be avoided most effectively it makes diving safer and diminishes the risks of fatal diving accidents. To benefit from argon, it is important to keep a sufficient layer of argon between the body and the drysuit. This is achieved by using thick layer of cloths under the drysuit, which in turn prevents the suit to squeeze against the body. Additionally, a repeated argon flush and squeeze procedure should be done to replace drysuit air with argon effectively before diving.

Our HRV study indicates that the first PNS increase at the beginning of a dive in cold water decreases quickly. We argue that the PNS increase is due to the trigeminocardiac part of the diving response, and its decreases quickly. PNS activity is most likely increased both by pressure and cold, but our study does not determine if the PNS activity increase comes to a plateau at some point. Therefore, we would suggest considering possible adverse effects of strong PNS stimuli especially on long, cold, and deep dives. At the beginning of dives in very cold water, to avoid strong concurrent PNS and SNS activation, which is linked to arrhythmia and sudden death, we would suggest a short adaptation phase. We also suggest it is prudent to recommend strict cardiovascular criteria for divers who dive in very cold conditions.

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The Arctic consists of the northernmost parts of our planet. The term “Arctic” stems from the Ancient Greek word “arktikós” - “northern of the Great Bear (Ursa Major)”. The southernmost area of the globe, famous for its penguins, is called “Antarctica” - “opposite to the Arctic”.

On the front cover of this thesis, a lost penguin in the North can be seen looking down in the direction of the Equator, and on the back cover another penguin in the South can be seen looking in the opposite direction. These penguins symbolize the universality of science. Although the name of the thesis is “Arctic diving”, science should not be seen as something confined to specific areas of the globe.

Like all present knowledge, my dissertation is a continuation of the efforts of others before me. Only with an understanding of their work has it been possible to plan these studies and to achieve something new. Hopefully my own research can open new paths and provide ideas for upcoming generations of researchers.

It is not easy to thank everyone involved in a project like this. The risk of forgetting to mention someone is too great, and therefore I won’t attempt to do so. This does not lessen my appreciation and thankfulness towards those who deserve it. I will make three exceptions: The commitment and helpfulness of my supervisors Anne Räisänen-Sokolowski and Kai Parkkola throughout the project has been greatly appreciated and cannot be left unmentioned. I would also like to thank my wife Anna, who has followed my work closely, for her support. I wish to dedicate this work to our firstborn child, Otto, who was born in January this year, just when I was adding my finishing touches to this thesis.

The ongoing Covid-19 pandemic has affected the whole world greatly. Healthcare professionals and researchers have gone to enormous efforts in order to improve the treatment of patients. Vaccines have been developed in record time. These achievements can certainly be defined as a triumph of science.

I cannot command winds and weather! But what I can do is study them - and with that knowledge I shall be able to adapt to them, to master the laws of nature and to use them to our advantage.

In the Arctic diving occurs in cold water throughout the year. At a depth of 20 meters sea/fresh water (msw/mfw) temperatures are 4°C even in the warmest summer. Cold is not only a discomfort factor for divers. It also impairs physical and cognitive performance, which in turn may jeopardize diving safety, and is one of the major risk factors for decompression illness (DCI).

In our study we looked for factors that influence diving safety in Arctic water temperatures and searched for possible ways to reduce the risks. Based on the results from our three studies we aimed to suggest improvements for cold water diving procedures. First, we studied special features of DCI in the Finnish diving population, and different factors associated with DCI.

Second, we investigated different thermal protection properties by comparing argon and air used as drysuit inflation gas. Argon is a widely-used passive method to reduce heat loss in cold water diving. Third, we studied the autonomic nervous system (ANS) responses to cold water diving with heart rate variability (HRV) measures. With results from these studies we aimed to give recommendations to make diving in Arctic conditions safer.